Light-Weight Materials Selection for High-Speed Naval Craft

by

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Submitted to the Departments of Mechanical Engineering and Civil and Environmental Engineering in partial fulfillment of the requirements for the Degrees of
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The potential materials for evaluation were selected using Naval Sea Systems Command (NAVSEA) references for the most current materials in use, or being evaluated, for light weight naval construction. The results demonstrate the feasibility of using the MDL method to select one or more materials based on desired mechanical and structural characteristics. The study also introduces the potential use of non-traditional materials in Naval Architecture, such as Ultra High-Performance Concrete Composite (UHP2C) DUCTAL ©.

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Dedication

To my son, Rowan.
I love you.

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Chapter 1. Introduction

1.1 Background and Significance

1.1.1 Definition of High-Speed Craft (HSC)

In modern Naval Architecture and Marine Engineering it has never been more imperative to optimize high performance light-weight materials for weight-critical ships. Typically, the structural weight of a ship is about one-third of its displacement, thus making the potential for substantial weight savings when considering light-weight materials over traditional steel construction. Advanced material technology is extremely important for weight-critical vessels that rely primarily on performance and maintainability such as in combat or for other military applications. The most typical weight critical class of vessel being those designated as high speed craft. High speed craft designs are numerous, and can vary greatly in shape and size depending on the specific mission of the vessel. The optimization of material selection for structural and non structural components is imperative when considering life cycle costs and performance. "High speed craft, unlike 'conventional' ships such as tankers, bulk carriers and containerships, are generally not variations on a single theme. There are dramatically different hull-forms (monohulls through trimarans and beyond), dynamic lift systems (semi-planing to hydrofoils) and propulsion types." [1]

There are several maritime societies that classify high-speed craft such as[1]:

(1) International Maritime Organization (IMO)

(2) American Bureau of Shipping (ABS)

(3) Bureau Veritas

(4) Det Norske Veritas (DNK)

(5) Lloyd's Register of Shipping

(6) Nippon Kaiji Kyokai

(7) Register Italiano Navale

The two societies' rules most recognized by the U.S. are those of IMO and ABS. The U.S. Navy in conjunction with ABS creates the rules for the combatant high-speed craft called Naval Vessel Rules (NVR). Due to the sensitive nature of combatant design requirements and limited distribution of NVR, the classification of navy high-speed craft for the purposes of this thesis will be referenced from the IMO and ABS.

1.1.1.1 International Maritime Organization (IMO) Definition of High-Speed Craft

The IMO is the United Nations' specialized agency responsible for regulating all matters pertaining to shipping. In 1994 the IMO developed the "International Code of Safety of High Speed Craft" (1994 HSC Code) to facilitate the future research and development of high speed craft.[2] It was later updated in 2000 to accommodate improved navigational equipment provisions.

In the (2000 HSC Code) IMO defines a "high-speed craft" as a craft that meets the following:[1]

$$V \geq 3.7\nabla^{0.1667}; \qquad (1.1)$$

In which the velocity, V is in meters per second and the displacement, ∇. is in cubic meters at the design waterline for saltwater. To express the velocity of the previous equation in terms of knots would be:

$$V \geq 7.16\nabla^{0.1667}; \qquad (1.2)$$

Where V represent the velocity in knots and ∇ is the displacement in saltwater in metric tonnes.[1]

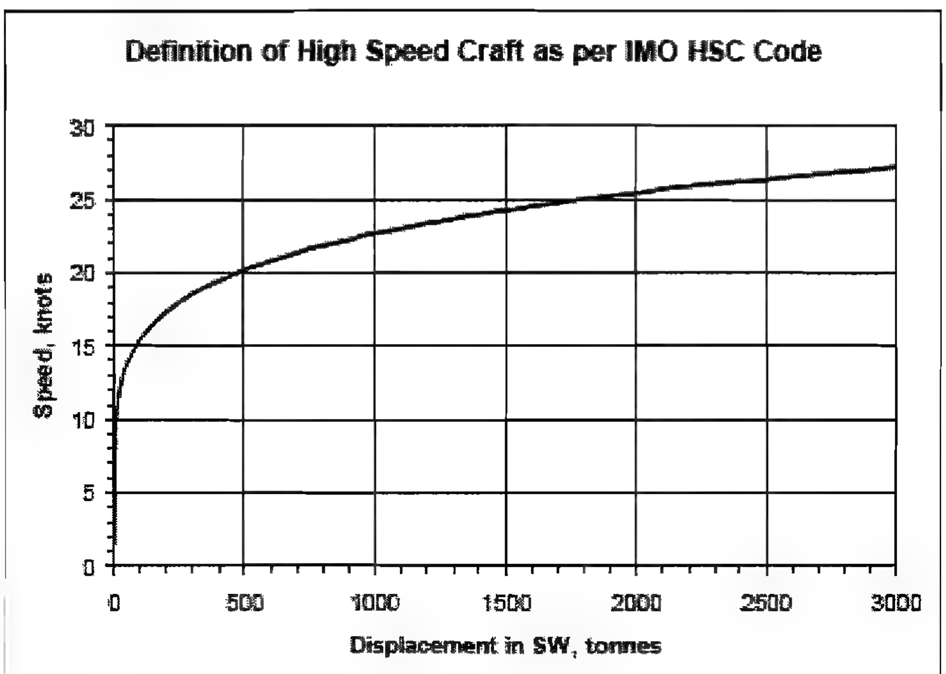


Figure 1.1: Curve Defining High Speed Craft per IMO HSC Code [1]

Using equation (1.2), one can see that Figure 1.1 charts the general displacement criteria for high speed craft versus the speed in knots. The speeds above the curve represent craft

that are classified as "high-speed" based on their respective saltwater displacement. Vessels meeting speed requirements below the curve at their respective saltwater displacement are not considered high-speed. For example, a craft with a saltwater displacement of 1000 tonnes would need to have a max speed greater than or equal to roughly 22.5 knots in order to be classified as a high-speed craft. It is important to note that the IMO chart above is strictly designed to provide a general guideline for classifying high-speed craft but can't be used for design purposes.

1.1.1.2 American Bureau of Shipping (ABS) Definition of High-Speed Craft

ABS has requirements for general high-speed craft ("Guide for Building and Classing High-Speed Craft" (HSC)) and also separate requirements specifically for naval craft ("Guide for Building and Classing High-Speed Naval Craft" (HSNC). [1] Both sets of guidelines apply to vessels made from aluminum, steel or composites.[1]

Where:

$$V/\sqrt{L} <= 2.36; \quad (1.3)$$

V = Velocity in knots

L = Length (meters) on the design waterline in the displacement mode

The table below shows how the ABS guidelines classify a given hull type with length requirements by using the velocity/length requirement above.[1]

Hull Type	Length Requirements
Mono-hull	< 130 m
Multi-hull	< 100 m
Surface Effects Ship (SES)	< 90 m
Hydrofoil	< 60 m

The primary difference between the ABS HSC and ABS HSNC is that the naval craft can further be broken down into three classifications and certain vessel classes require direct analysis. The table below shows all the classifications of ABS high-speed craft.

High Speed Class Types	**Description**
HSC	Unrestricted Service
Naval Craft	Assigned to a naval vessel that is intended to operate in the littoral environment, but is capable of ocean voyages
Coastal Naval Craft	Assigned to a naval vessel that is intended to operate on coastal voyages with a maximum distance from safe harbor of 300 miles
Riverine Naval Craft	Assigned to a naval vessel that is intended to operate in rivers, harbors, and coast lines with a maximum distance from safe harbor of 50 miles

Table 1.1: ABS HSNC Classification Types [3]

With the exception of Riverine Naval Craft, direct analysis is required for all high-speed class types and the ABS requirements for direct analysis are as follows.

Craft Type	Length	Speed
Naval Craft	All	All
Coastal Naval Craft	>= 45 m	All
	< 45 m	40 knots
Riverine Naval Craft	None	None

ABS defines "direct analyses" as using an acceptable finite element method computer program to appropriate to reflect adequately the behavior of the structure. "The loads to be applied to the structural model are to be based on consideration of the design values, deck cargo and similar internal loads in the hull (accounting for dynamic effects as appropriate), the external pressure loads and distribution… and appropriate wave induced hull girder bending moment and shear force effects." [3]

Using equation (1.3), the ABS high-speed classification curve is shown in Figure 1.2. Designs that fall within the area under the curve use ABS rules for non-high speed craft and the area above the curve represents those that meet ABS guidelines for HSC.

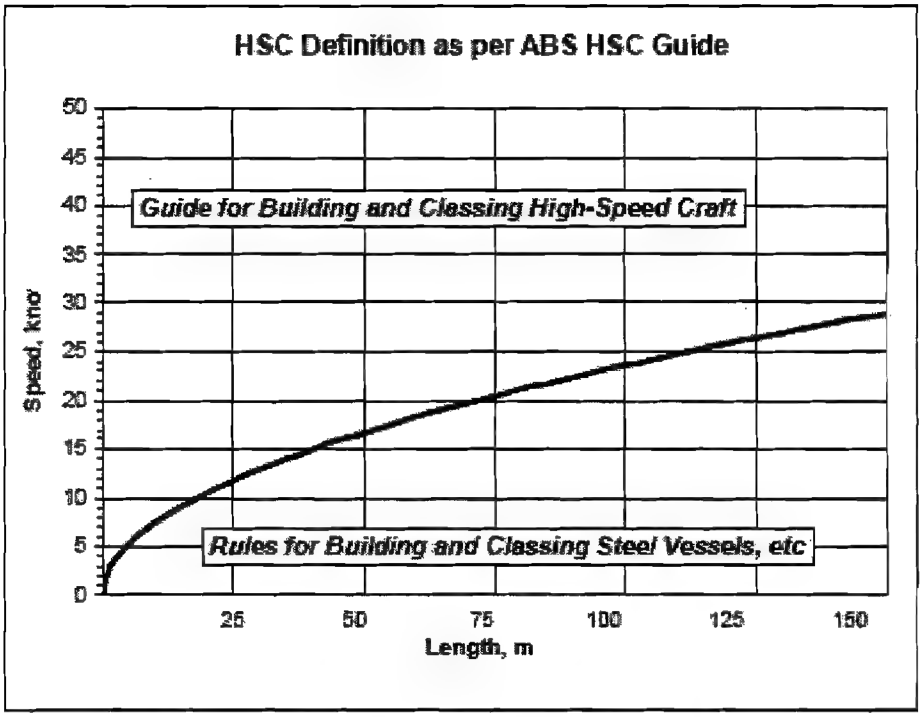


Figure 1.2: Definition of HSC per ABS HSC Guide [1]

Although IMO and ABS HSC requirements are similar in qualitative description, ABS rules will be the governing reference for "High-Speed Craft" in this thesis. Further, due to the naval architecture aspects of this thesis, specifically ABS rules for High Speed Naval Craft (HSNC) will be utilized as the defining guidelines and requirements where necessary.

1.1.2 General Requirements for use of Light-weight materials

The reference governing vessels in the United States for the current use of materials including light-weight materials, specifically Aluminum and Fiber Reinforced Plastics, is ABS, ref [3]. There are currently no guidelines or provisions for other lightweight materials such as the metallic and hybrid material sandwich structures, but ABS does

state that all other materials not covered by their regulations will be assessed and approved or disapproved based on application and review. The overall purpose of the ABS regulations and guidance is to ensure the materials production processes, testing, evaluation, performance and safety criteria are met.[3]

1.1.2.1 ABS General Material Requirements for Aluminum

Chapter 5 of reference [3] covers aluminum material requirements for hull construction of High-Speed Craft. A summary of aluminum requirements from ABS are presented below.

- There shall be no linear defects in the material and/or welds
- No planar or volumetric defects are permitted
- Surface flaws that may cause injury or inadequacy for application are not permitted
- Discoloration alone is not a reason to reject an otherwise approved aluminum material

Specific material evaluations associated with the ABS guidelines include tension tests, heat treatment specifications, chemical composition, corrosive testing, and welding.[3]

1.1.2.2 ABS General Material Requirements for Fiber Reinforced Plastics (FRP)

Chapter 6 of reference [3] covers FRP composite material requirements for hull construction of High-Speed Craft. A summary of FRP materials is listed below.

Acceptable Fiber Reinforcement [3]:

- E glass
- S glass
- Carbon
- Aramid (Kevlar)
- Hybrid reinforcing materials are also acceptable

Fiber	Tensile Strength (MPa)	Tensile Modulus (GPa)	Ultimate Elongation (%)	Cost U.S.$/kg (2005 $)
E-glass	3,450	72	4.8	2.60
S-glass	4,600	87	5.7	13
Kevlar ®	3,600	124	2.9	20
Carbon	2,400-4,800	230-390	.38-2.0	20-80

Table 1.2: Raw Fiber Properties [25]

Laminates [3]:

- Unsaturated general-purpose polyester resin and alternate plies of E-glass
- Fiberglass mat and fiberglass-woven roving fabricated by the contact or hand lay-up process

Resins [3]:

- Polyester – Isophthalic, Orthophthaic, or Dicyclopentadiene may be used
- Vinyl Ester – Extremely chemically resistant finishes, high abrasion resistance, can also be made waterproof
- Epoxy – Should not be used in conjunction with Polyester or Vinyl Ester. Best used by itself
- Phenolic – Is not suitable for structural applications, but does have good fire retardant characteristics

Resin	**Tensile Strength (ksi)**	**Tensile Modulus (ksi)**	**Ultimate Elongation (%)**	**Est. Cost ($/lb) (2005 $)**
Orthophthalic (Polyester)	7.0	5.9	.91	1.05
Discyclopentadiene (Polyester)	11.2	9.1	.86	1.11
Isophythalic (Polyester)	10.3	5.7	2.0	1.36
Vinyl Ester	11-12	4.9	5-11	2.30
Epoxy	8.0	5.3	6-8	7.00
Phenolic	435	7.8	N/A	1.60

Table 1.3: Resin Properties [25]

Additives[3]:

- If additives are used to increase the various performance characteristics of the resin, such as fire resistance or waterproofing, they must be applied at the manufacturing plant and tested accordingly
- If the additive must be applied after the resin has cured, the builder must ensure that the process meets manufacturers implicit guidance

Specific material tests and evaluations associated with the FRP ABS guidelines include fabrication processes, building processes, quality control, structural analysis, and repairability.

1.2 Light-weight Materials Used in Naval Construction

1.2.1 Proven High Performance Light Weight Materials

As the U.S. Navy develops its next generation structural design and construction of weight-critical ships such as the Littoral Combatant Ship (LCS) and Joint High-Speed Vessel, more and more demands are being placed on material property requirements in terms of performance, weight, and cost. High Performance light-weight materials can provide as much as 40% of a ships structural weight (SWBS 100) reduction when compared with traditional plate and beam steel construction.[4]

Although weight savings are the most obvious benefit to these types of material, they can also provide other naval architecture benefits such as:

- Higher strength to weight ratio (Less Dense)
- High durability and increased fatigue strength
- Good shock resistance
- Reduced noise and vibration properties
- Low thermal conductivity (great thermal insulators)
- Flexibility in design (Large molded pieces can be easily made)
- Lower life cycle maintenance costs (i.e. less paintings, corrosive resistance, etc.)

Lightweight materials such as aluminum and titanium have been used in the construction of weight critical ships in the past. However, more advanced material such as composites and lightweight metal sandwich materials are quickly becoming more viable solutions to the need for a strong, durable, light-weight material to replace traditional steel and other monolithic metal materials.

1.2.1.1 Aluminum

Aluminum is relatively inexpensive as a raw material, roughly one third the density of steel, and single skin construction offers an estimated 30% reduction of a ship's structural weight (SWBS 100) over steel, thus making aluminum the material of choice for weight critical ships. If a more proven technology is preferred and there isn't a desire to perform costly research and development then single skin aluminum construction is the optimum material for vessels under 300 ft. However, the disadvantages of single skin aluminum construction can not be ignored. Aluminum does not have adequate strength for large in-plane and lateral loads required for ships larger than 300 ft, requires numerous support

frames and stiffeners, poor fire resistance characteristics, and requires improved joining technology to avoid large deformations translating to higher manufacturing costs.[5]

Aluminum sandwich construction for ship plating offers the potential to provide even higher weight savings than single skin construction due to its low density construction while maintaining high rigidity and strength. The increased strength presented by the low density sandwich construction provides the need for less scantlings while at the same allowing for increased frame spacing, both which reduce overall structural weight and construction costs. Although aluminum sandwich construction is promising, it still in the developmental stages and like single skin construction it has strength limitations, joining issues, can not be easily repaired at sea, and has a low fire resistance.[5]

1.2.1.2 Composites

One of the primary reasons why the Navy is turning to composite materials for use in current and future ship design is to reduce topside weight, decrease life cycle maintenance costs, and their ease of manufacturing. The increasing role of high-speed naval craft is a fine example of why the Navy is calling for lighter-weight materials that are durable and easy to manufacture. Composite materials fit the bill, because their cost to weight savings benefit can be seen in a wide variety of applications within the naval engineering industry. When compared with steel, composites have a higher strength and hardness, and for the same strength are lighter than aluminum.[4]

Composite materials can be defined as materials that consist of fiber reinforcements embedded in a resin mixture that forms a hardened matrix structure.[4] The fibers used in composites are generally consist of carbon, Kevlar, or glass. The resin used can include polyester, vinyl ester, epoxy, or phenolic. Although composites have been used in the U.S. Navy since the 1940's with the fiberglass composite small boats and mine countermeasure vessels, however they have not been used extensively in ship architecture until only recently. Future use of composites will be seen extensively on topside structures of the DD(X), LCS designs, air cushion vehicles, and high speed connectors. There are numerous advantages of using composites in naval architecture as seen in the following list[4]:

-High strength and rigidity

-Higher strength to weight ratio (Less Dense)

-High durability and increased fatigue strength

-Good shock resistance

-Reduced noise and vibration properties

-Low thermal conductivity (great thermal insulators)

-Flexibility in design (Large molded pieces can be easily made)

-Lower life cycle maintenance costs (i.e. less paintings, corrosive resistance, etc.)

Based on the aforementioned beneficial characteristics to naval architecture composite materials will continue to become an extremely viable alternative, if not the norm over steel and aluminum.

Limitations of Composite Materials in Naval Architecture

As with most new materials used in industry there are several limitations to the use of composites. Joining technology limitations tend to be the primary technology gap concern. Current methodologies utilize mechanical fasteners and adhesives to join composites to steel, and even composites to composites joints. The fasteners and adhesives are expensive and can provide major maintenance concerns over time.[4] Although composites are fairly easy to manufacture, the costs involved are relatively high and they require a higher level of expertise to fabricate. However as they become used more extensively the fabrication costs will inevitably decrease. Composites also have relatively low compression strength so they are not recommended for hulls greater than 300ft.[4] Various defense contractors are looking at hybrid hulls that will combine steel with composites to meet the required loads while still being able to capitalize on the benefits of composites. Finally, composite materials, like their aluminum counterparts tend to have limited fire protection capabilities – carbon fiber reinforced plastics have a relatively low ignition temperature (384 degrees C/723 degrees F) and may delaminate creating a weaknesses or structural failure.[4]

1.2.1.3 Light-Weight Metallic Sandwich (LMS)

The U.S. Navy's use of hybrid materials, in particular LMS construction, started in 1978 with the 6.2 Topside Weight Savings Program.[5] The Naval Sea Systems Command (NAVSEA), which is the engineering design, acquisition, and procurement arm of the U.S. Navy, has been able to prove that the material does reduce topside weight considerably over traditional steel construction and in some cases over single skin

aluminum. The reduction comes through the hybrid's ability to exhibit the characteristics of low density construction while maintaining the strength obtained from combining two or more materials. LMS structures also provide other benefits due to their lightweight and durable nature which include reduced fabrication costs because there is no need for secondary stiffening and outfitting, an increase in overall compartmental volume because the LMS simply takes up less space than traditional plate and beam structure, and finally reduced maintenance costs because of the use of corrosion resistant materials such as stainless steel and aluminum. [11]

LMS can reduce topside weight roughly 40% over conventional steel construction and 25% over thickened single skin aluminum.[11] LMS panels can be created using a variety of materials such as stainless steel, aluminum, and titanium or a combination thereof. The basic construction of an LMS is shown in Figure 1.3:

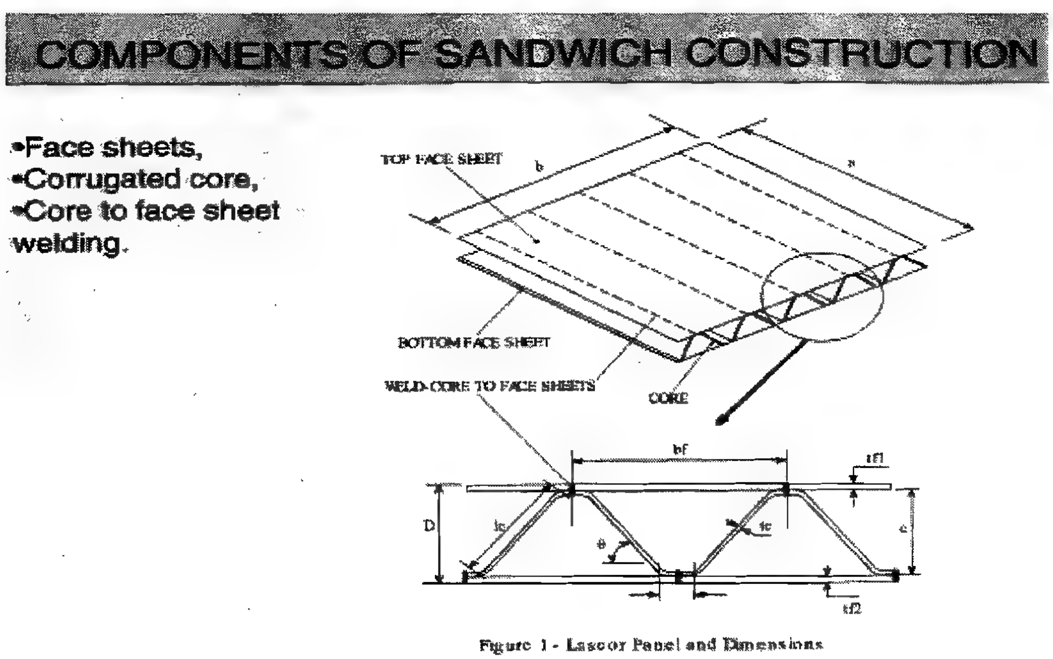


Figure 1.3: Components of LMS [7]

As you can see in Figure 1.4 and Figure 1.5 below, the LMS design saves volume and provides less complicated support system integration such as piping and HVAC systems.

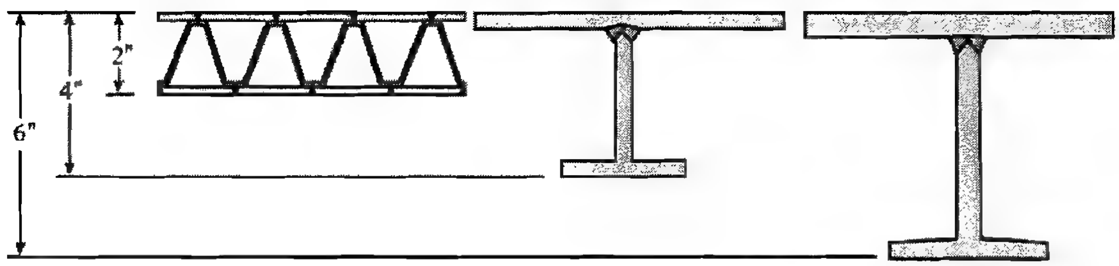


Figure 1.4: LMS vs. Conventional Beam Stiffened Plate [7]

Although Figure 1.4 is strictly a visual representation and is not an equivalent strength comparison, it demonstrates the differences between LMS construction and typical beam and tee configurations used in traditional steel structures. It also demonstrates LMS's potential to minimize the structural footprint thus saving valuable interior volume and thus less-complex outfitting which can be more clearly seen in the figure below.

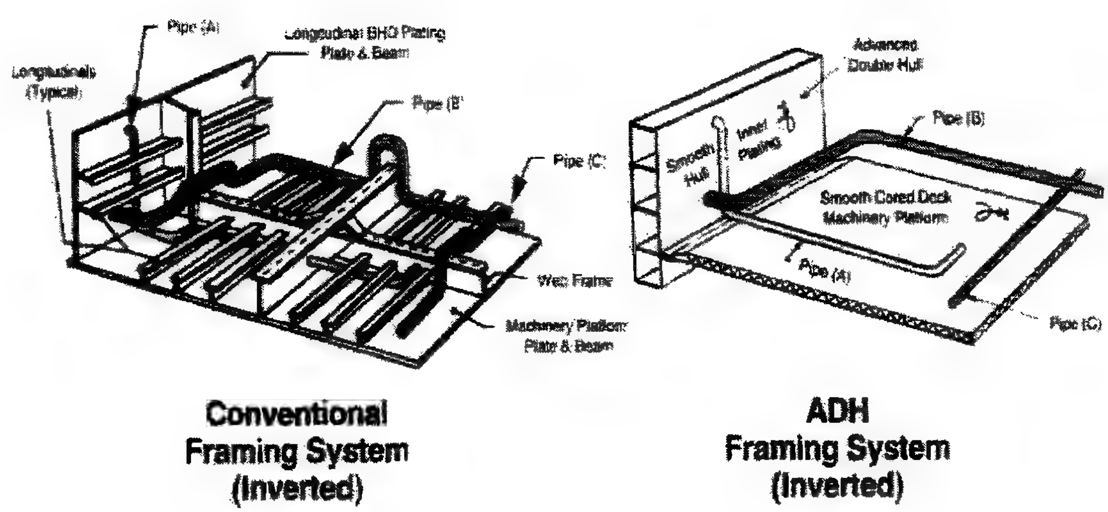


Figure 1.5: Outfitting of Beam Stiffened Plate vs. LMS [7]

Although stainless steel LMS is a promising material to be used in future structural applications, there are several fabrication issues that must still be addressed. The construction of the corrugated core presents problems due to the precise tolerances required for welding the sandwich plates against the core structure.[7] When an imperfection is made during the welding process it creates a fatigue weakness in the panel thus making the process time consuming and costly.[7] This material and the processes to fabricate large quantities are currently being closely examined due its intended use in the construction of the Littoral Combat Ship. In addition, the fatigue performance of sandwich materials must be further researched as their performance when put through real hydrodynamic and operational loads has not yet been extensively evaluated and defined.

1.2.2 Applications of Light-Weight Materials

Until recently, the application of light-weight materials was primarily found in the aerospace industry. Now, light-weight materials are being used extensively in all areas of engineering where specific material performance characteristics such as weight and durability are required. Examples of more recent applications include bridges, roads, machinery, tools, buildings, decking, furniture, automobiles, bicycles, medical devices, and any other type of general structure. As mentioned in previous chapters, the use of light-weight materials in the marine industry is growing as well. Aluminum is currently the most widely used light-weight material in naval architecture. Aluminum is an abundant material, can be easily manufactured, non-corrosive, and is one third the weight of construction grade steel. Although, aluminum has many of the characteristics that the

marine industry requires of light-weight material naval designers throughout the world have experimented and applied other light-weight materials such as titanium, composites, and other high performance light-weight material in limited quantities.

Although not specifically to reduce overall weight, the Navy's first use of materials other than monolithic metals occurred in the 1940's with the design of the fiberglass composite small boats and then later the MHC 51 class mine-hunters. The composite construction enabled the hulls to be non-ferrous to counter mine fields and to be light-weight for ease of transportation of the vessels to forward operating areas and to increase overall fuel efficiency. As material technologies increased, so too did their use in all areas of naval architecture. Composites have now become the primary light-weight material used on naval vessels to reduce weight. New material systems are required as a result of advanced performance criteria spelled out in the DD(X) (next generation destroyer) program and other Navy ships. These requirements call for reducing the weight of ships, especially structures above the waterline and on upper decks (topside). Thus, there is an increased demand to use composite materials in the fabrication of topside structures like helicopter hangers, control rooms, and mast enclosures.

1.2.3 U.S. Navy's Application of Light-Weight Material

1.2.3.1 USS ARTHUR W. RADFORD – Mast Enclosure

In 1998 the U.S. Navy's first-ever advanced hybrid composite structure was installed aboard the SPRUANCE Class Destroyer USS ARTHUR W. RADFORD.[8] The composite structure known as the Advanced Enclosed Mast/Sensor (AEM/S) System, is

used to house the major antennas and other electronic sensor gear. The AEM/S System is a hexagonal structure that measures 88' high and 31' at the largest sectional diameter.[8] Its purpose is to enclose existing radar and providing important signature and other operational benefits.[8] The AEM/S System protects them from the weather and allows for maintenance to be performed without having to worry about environmental factors.

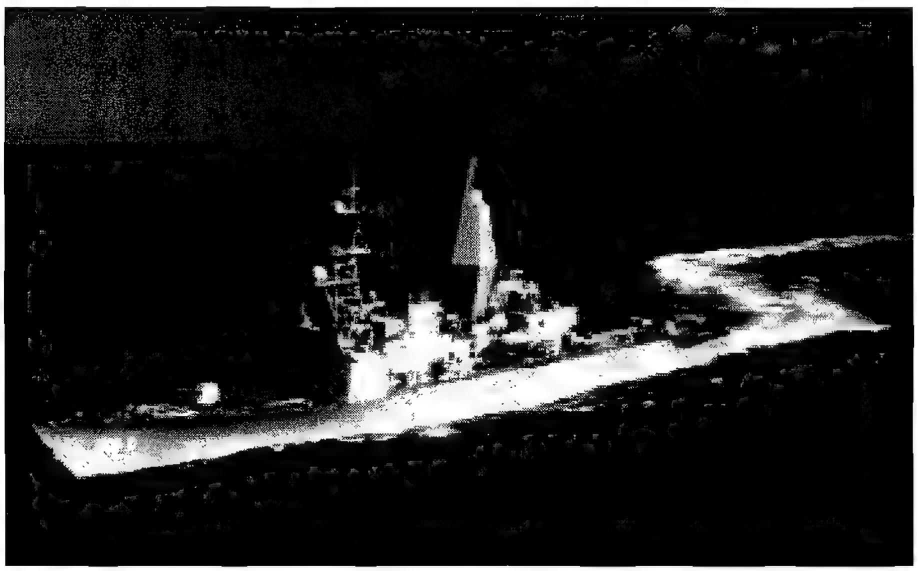


Figure 1.6: USS ARTHUR W. RADFORD (DD 968) with AEM/S Mast [8]

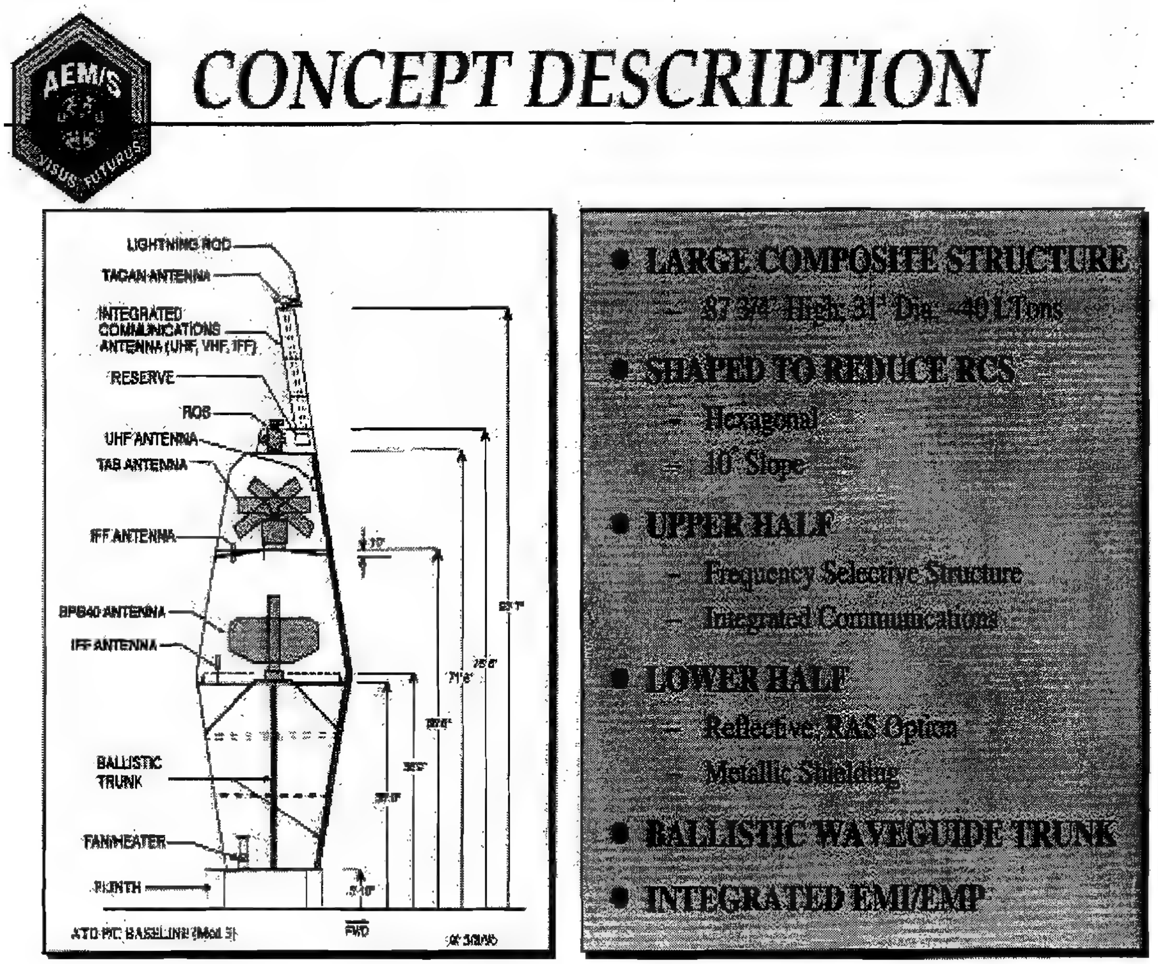


Figure 1.7: AEMS/S System Description [8]

The AEM/S system uses an advanced composite hybrid material that allows for the selective frequency of own ship sensors while blocking unwanted frequencies. Operational testing has also provided proof that the composite masts increase sensor performance due to its ability to block unwanted electromagnetic and environmental noise. The enclosed mast also allows for less downtime due to increased maintenance availability.[8]

1.2.3.2 LPD 17 – SAN ANTONIO Class – Mast Enclosure

LPD 17 Class warships have two large octagonal composite structures used to enclose the ship's radar and communications. Similar to the USS RADFORD's AEM/S system, the LPD 17's masts significantly reduces the ship's radar cross section and protects electronic equipment from exposure to the elements - reducing maintenance workloads - and improves sensor performance.[9]

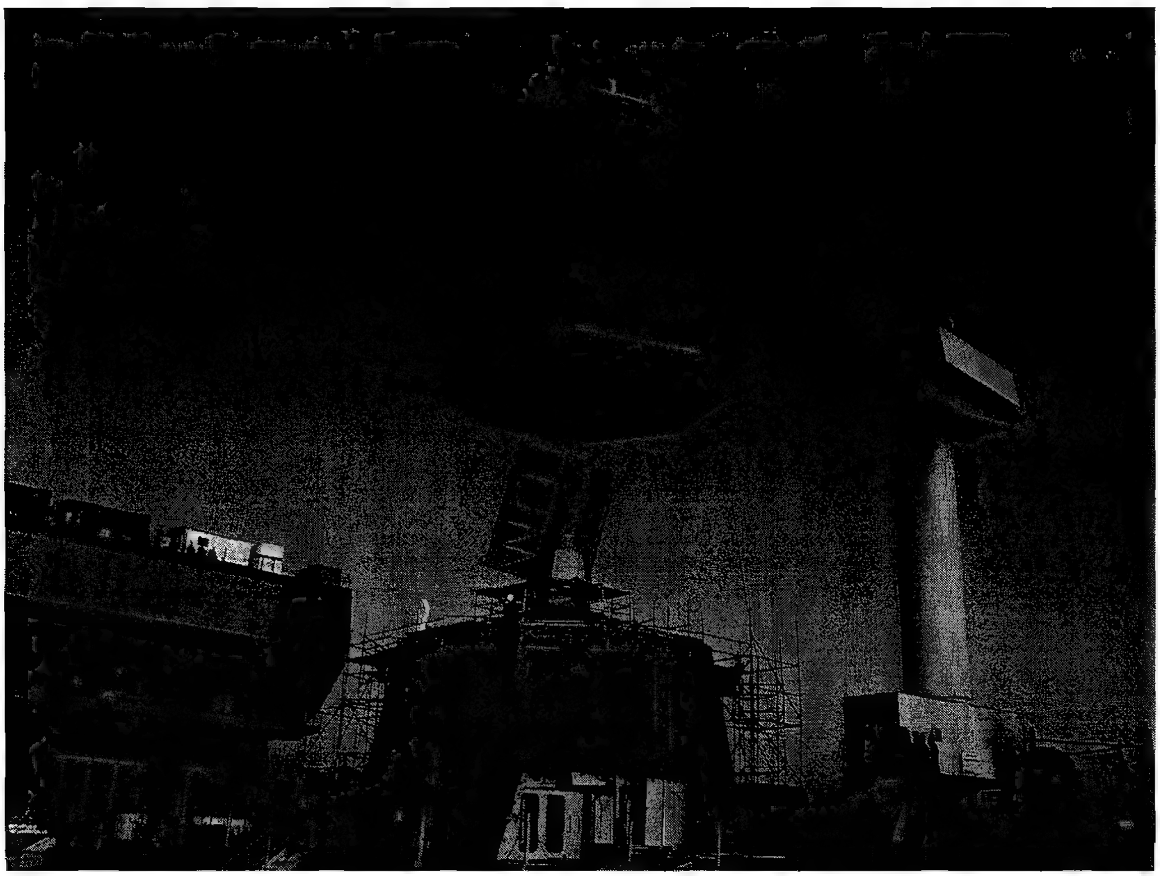


Figure 1.8: LPD 17 Aft AEM/S System Installation [8]

"The masts are the largest composite structures ever installed on U.S. Navy steel ships and represent a revolutionary advancement in topside engineering".[9]

1.2.3.3 Aircraft Carrier Deck Edge Elevators Doors and Elevated Decks

Light-weight stainless steel corrugated core sandwich material has been successfully installed on aircraft carriers deck edge elevators doors and elevated decks to reduce weight.

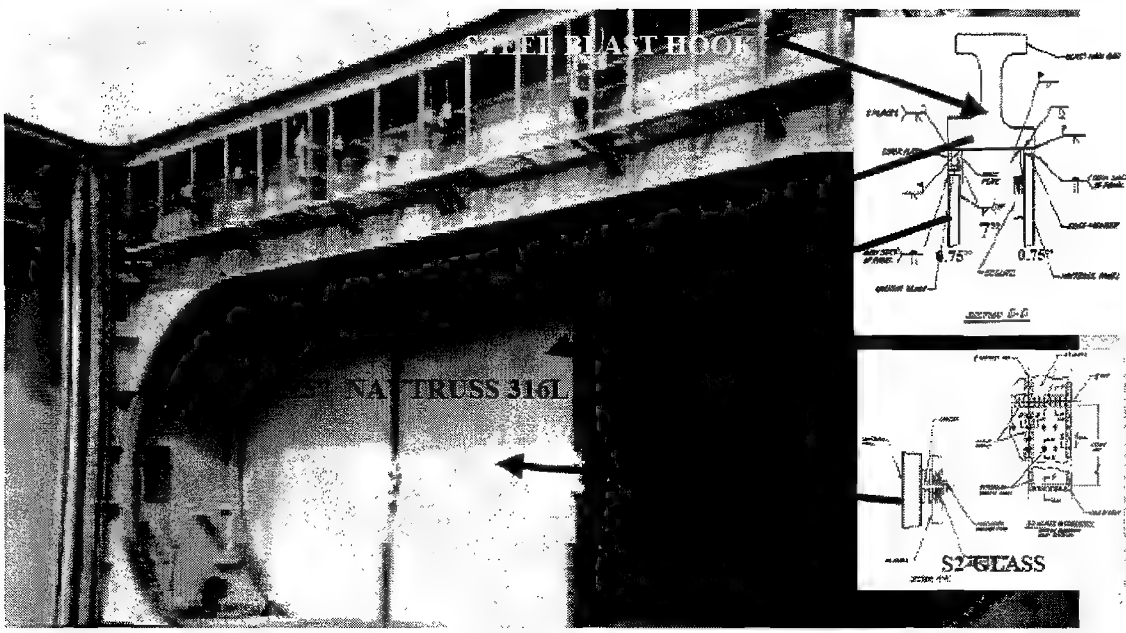


Figure 1.9: CVN 66 LMS Deck Edge Elevator Doors [10]

"The use of LMS has reduced the weight of elevator doors by 45% or 20 LT over existing conventional steel plate beam construction. In aircraft 02 level design LMS panel construction saves 5.54 lbs/sqft over conventional steel plate beam construction".[6] In addition to being light-weight, LMS panels meet NAVSEA strength requirements as well as survivability requirements of military standard Grade A shock impact. Figure 1.10: below shows the weight comparison and differences in physical design between LMS and conventional steel plate construction. Notice that the LMS panels do not require the insulated wrapped stiffeners.

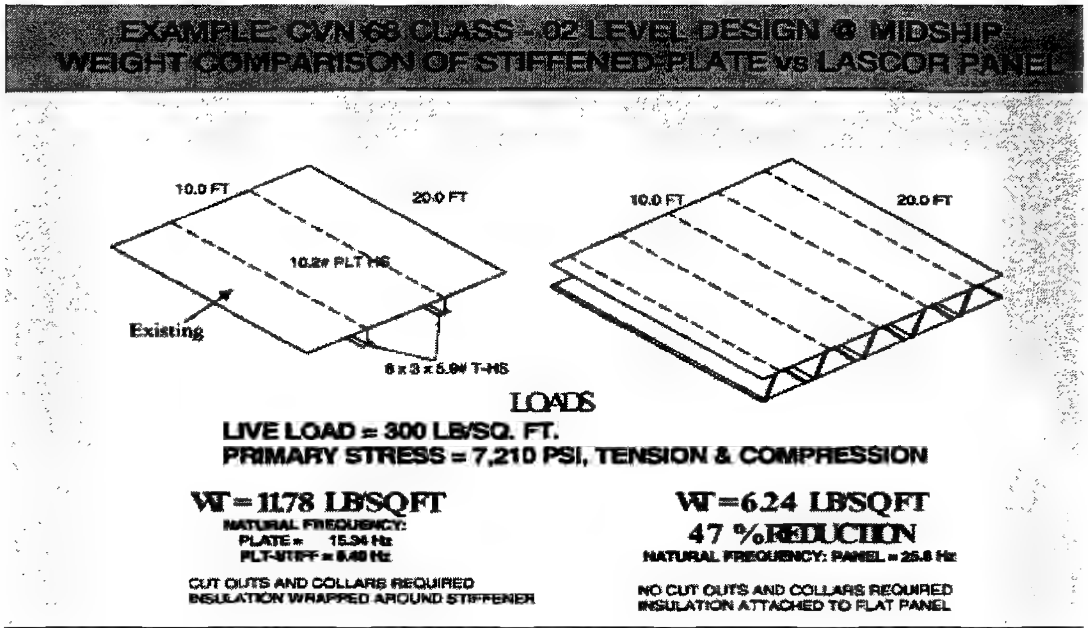


Figure 1.10: CVN 68 LMS 02 Level Deck [5]

1.2.3.4 AEGIS Class Cruiser - Exhaust Uptakes

LMS panels can also be shaped to from more complex shapes such as curved surfaces and cylinders. Core thicknesses can be tailored to meet strength and performance requirements of various structures.[10] An example of their use in a more complex structure can be seen in Figure 1.11 in which the material is used to fabricate the Aegis Class guided missile cruiser exhaust uptake. The LMS exhaust uptakes manufactured by NAVTRUSS© save approximately 32 light tons over the cruisers traditional steel design.

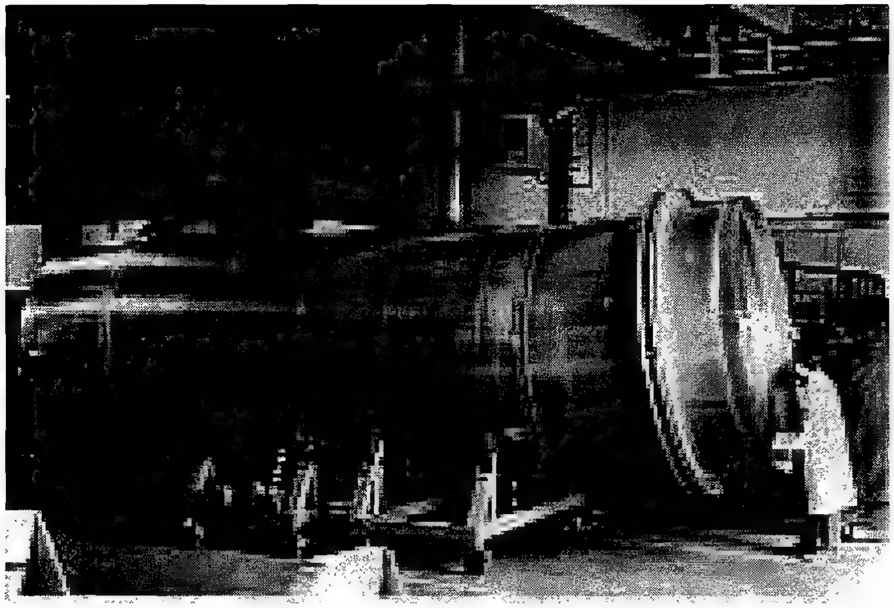


Figure 1.11: Aegis Class Cruiser LMS Exhaust Uptake Made By NAVTRUSS © [10]

1.2.3.5 DDG 51 Class - Helicopter Hangar Doors

NAVTRUSS LMS panels used on DDG 51 Class Destroyer Flight II helicopter hangar doors reduce traditional aluminum constructed hangar doors by 40%.[11]

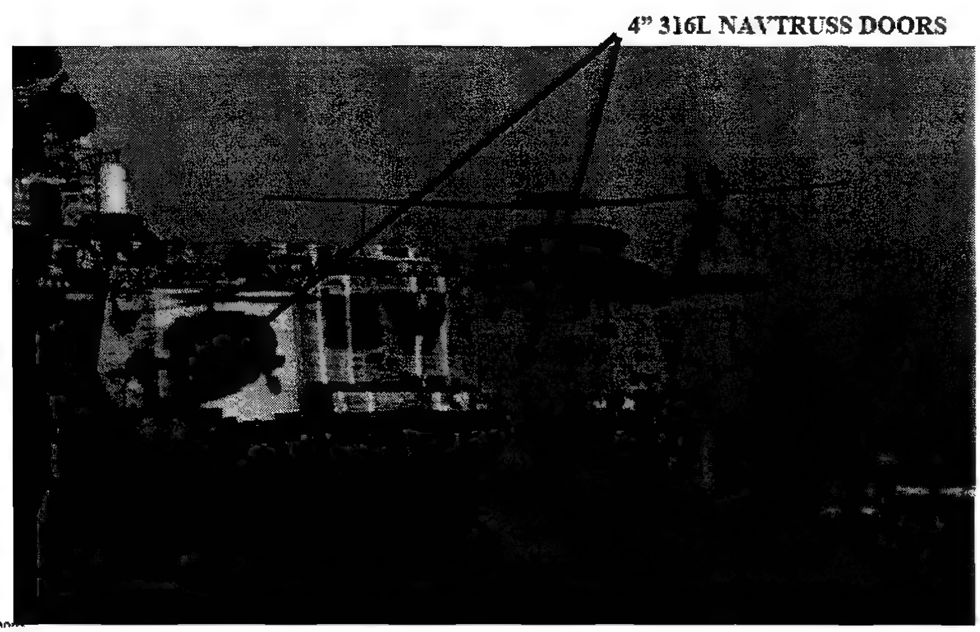


Figure 1.12: DDG 51 Class Helicopter Hangar Doors Made From Steel LMS [10]

Although light-weight materials have been exclusively used on small high speed craft for many years, their use is increasing exponentially on all classes and sizes of ships. Their performance-enhancing and weight savings characteristics bring vital engineering value to naval architecture and marine engineering.

Chapter 2. Material Selection Based on Light-Weight Material Properties and Characteristics

"Truly successful decision making relies on a balance between deliberate and instinctive thinking"

- Malcom Gladwell, Blink: The Power of Thinking Without Thinking, 2005

2.1 Introduction

Commercial and military high-speed craft require development of low-cost, high-strength/ lightweight materials. Thus there is a current preponderance of light-weight and high stiffness materials being used for secondary structures such as deckhouses, helicopter hangars, weapon enclosures, elevated decks, etc. and for primary structures of vessels less than 100 meters. There are a myriad of selections and combination of materials used for light-weight and high performance on weight critical vessels. Their prolific use, sensitivity to cost, and specialized end-user performance requirements are just a few reasons behind the need to develop tools that help optimize material selection in the early stages of design.

Material selection is vital to naval architecture because there are applications to structural and nonstructural components in the design of a vessel. A material selection process can be effectively used in the selection of ship plating, beams, stiffeners, columns, doors, decks, ventilation ducts, removable modules, and advanced hull forms. The fundamental

issues designers face when selecting material for high-speed craft can fall into several or all of the areas below.

- Vast number of materials to select from
- Cost considerations (Raw/Fabricated)
- Ship performance requirements
- Application of material
- Material limitations/trade-offs
- Maintainability (20-30 year life)

In most cases, performance and cost are the primary parameters when selecting materials for a given ship design. Aside from the aspects concerning technology gaps, the aforementioned philosophy of cost and performance being the primary issues when creating a design can be seen historically by the predominate use of steel on ships of all sizes and exclusively on ships that exceed 130 meters. Steel is relatively inexpensive and provides an acceptable level of performance. However, over the last decade there has been a marked increase in use of all kinds of materials based on their properties and potential advantages for specific applications. A valid and dependable material selection process will allow the designer to initially investigate all of the material options being evaluated for weight-critical ships and their applications in an efficient and precise manner.

2.2 Ashby's Material Selection in Mechanical Design

2.2.1 General Material Selection in Design

In the design of any mechanical systems the material that it is constructed from plays a significant role in how the system will perform, wear over time, cost, weigh, and appearance. Although in some cases the material properties can easily be interchangeable without having adverse effects on some or all parameters above, it is the designer's role to determine which attributes of the design requires optimization and which attributes can be sacrificed at little or no diminishing value to the product. For example, in designing a ship's hull the naval architect desires the hull to be stiff, strong, light-weight, and durable. Thus, for stiffness the designer will require a material with a high Young's Modulus, E, for strength, a high value for the elastic limit, σ_y, for light-weight a low density, ρ, and for durability, a high fracture toughness, K_{ic}. If the initial material chosen lacks in any one of the design requirements, then a new material can be chosen that increases the value of the inadequate variable without having to change the design. However, the designer must realize that more often than not there are property tradeoffs between each material. In this situation, it is paramount that designer select the material that is able to optimize all variables of the design requirements.

There are four basic steps in the material selection process [12]:

- Determine design objective and then translate requirements into desired material characteristics
- Eliminate the materials that do not meet proscribed design criteria
- Rank materials based on how well they meet design criteria
- Verify results by conducting research that proves findings

When selecting materials it is important to take into consideration not only the type of material but how it is being applied in the final design. Some systems require a single material while others require a combination of two or more materials. Monolithic material selection is slightly different than that of multi-materials. Figure 2.1 depicts the flow path of monolithic material selection. The first step in the process is to determine the design objectives and translate the design requirements into material constraints. Following the selection of materials to be evaluated, a screening process is initiated to eliminate the materials that do not meet the given design constraints. Next the materials are ranked based on optimization of desired properties. The design constraints provide input during the screening and ranking process. From this process a designer is given a subset of potential materials that can be examined more in depth in order to find the optimum solution.

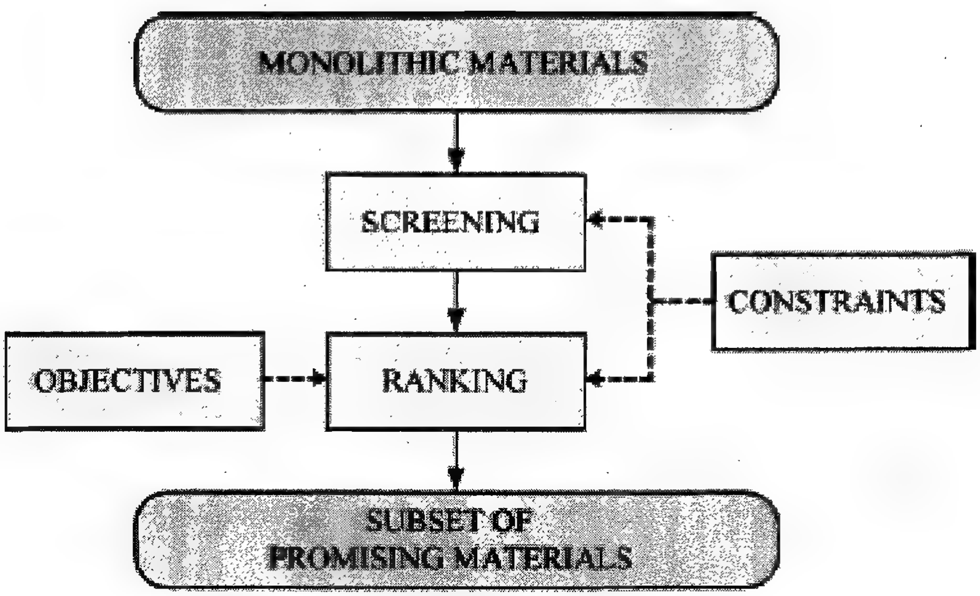


Figure 2.1: Monolithic Material Selection Decision Flow Path [14]

When the material selection process calls for the combination of one or more materials, ref [14] proposes a multi-material synthesis to be incorporated into the monolithic material selection flow path. The multi-material synthesis is virtually the same as the monolithic material selection however it contains three addition steps that receive inputs from the monolithic material properties data, objectives, and design constraints. After selecting the material combinations to be evaluated, the designer performs a multi-material configuration step (i.e. selection of sandwich, laminate, etc.) thus determining the form of the multi-material (i.e. face and core or fiber and matrix). The last step in the proposed multi-criteria material synthesis is the prediction of properties of the combined materials. The last step receives input form the constraint data and the resultant output is sent back to the ranking step of Figure 2.1.

Figure 2.2 shows the proposed multi-material selection process.

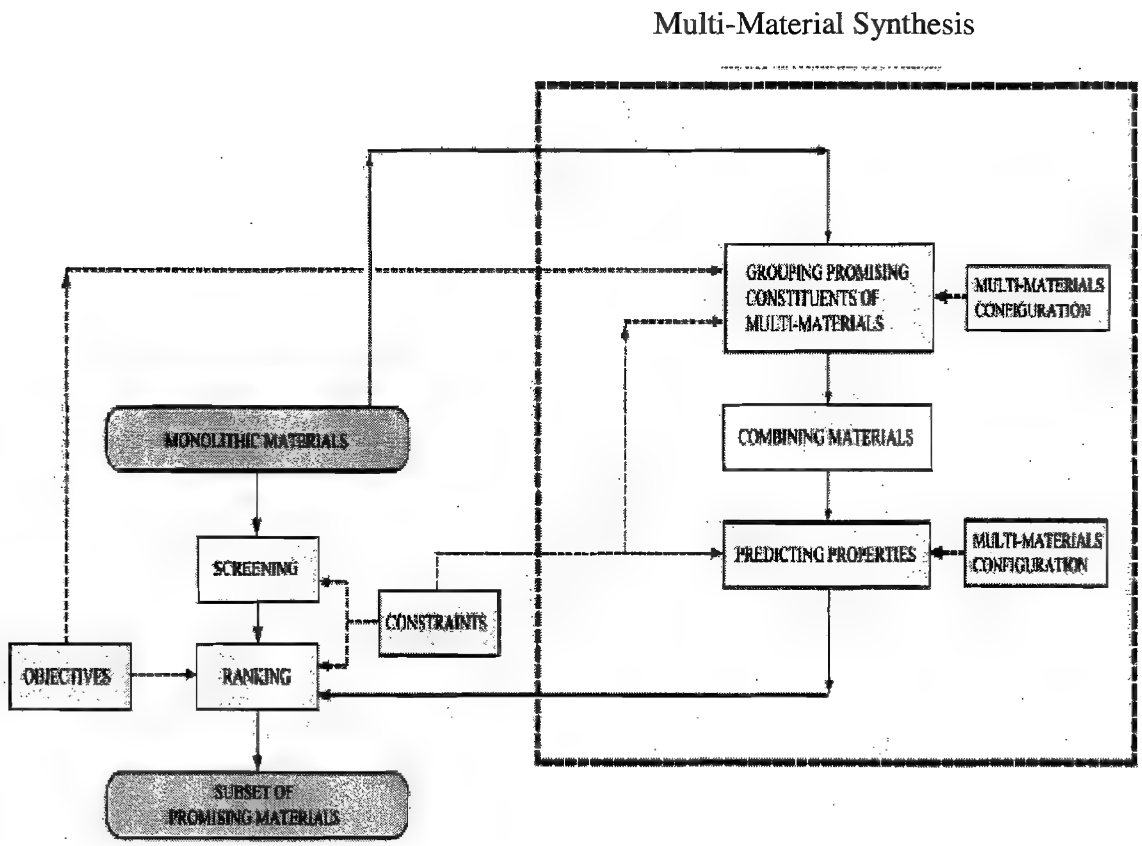


Figure 2.2: Multi-Materials Selection Decision Flow Path [14]

In ref [13], Ashby outlines basic material properties that are important to selecting the right material for a given mechanical system. The figure on the next page shows the four categories and the associated units of each subcategory.

General

Weight: Density ρ, Mg/m^3

Expense: Cost/kg C_m, \$/kg

Mechanical

Stiffness: Young's modulus E, GPa

Strength: Elastic limit σ_y, MPa

Fracture strength: Tensile strength σ_{ts}, MPa

Brittleness: Fracture toughness K_{ic}, $MPa.m^{1/2}$

Thermal

Expansion: Expansion coeff. α, 1/K

Conduction: Thermal conductivity λ, W/m.K

Electrical

Conductor? Insulator?

Figure 2.3: Ashby's Four Categories of Basic Material Properties [13]

The basic material properties are the foundation parameters for material selection. The properties above are simply used to narrow the field of materials down to the most basic requirements for the mechanical system in question.

From this initial step, a designer can select or deselect a material based on their general property (cost and weight), mechanical property (ductility and brittleness), thermal property (expansion and conduction), and whether the material is more of an electrical conductor or insulator.

2.2.2 *Goal of Design*

According to Ashby, the goal of design is to create a product that performs a given function efficiently, cost effectively, and safely. He suggests that the process of material selection to meet the aforementioned design goals can be broken down into two phases. The first phase is the characterization of the material(s). In this phase general materials are classified and their respective properties are analyzed and compared. The second phase of the goal of design is the selection and implementation of the material. In this phase the design data from the first phase is used to select the intended material based on the optimization of the material's properties with the design requirements. The ideal application is then determined based on the design data. After a favorable economic analysis of applying the material to a given application is performed testing and implementation of the material can begin. The materials to be evaluated are tested under specific load tests that are modeled after the loads and types of loads that the mechanical system, for which they are intended, will undergo. Generally, these materials are tested at much higher loads to allow for safety factors and failure mode determination. [13]

2.2.3 *Ashby's Material Selection Charts (MSCs)*

Performance can be maximized by selecting the right material for the right application. Each material behaves differently and has limitations so it is important to initially consider the widest range of materials. Ref [13] provides Ashby's Material Selection Charts that compare a wide range of materials in terms of their respective properties. The materials are compared using two properties at a time and are organized in the manner shown in Figure 2.4.

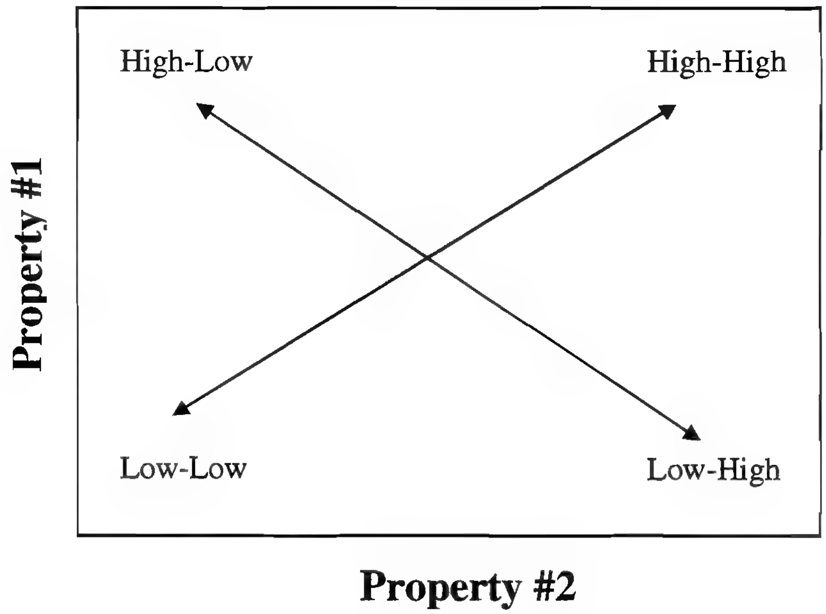


Figure 2.4: Ashby's Material Selection Chart Organization

The charts can be useful to find the general layout of material choices based on performance requirements. The charts can also be used to specifically target materials that are grouped about a region by breaking the chart into sub-ranges in which a specific area of the chart is analyzed.

Within the Material Selection Charts the materials are grouped by classes as shown below in Figure 2.5.

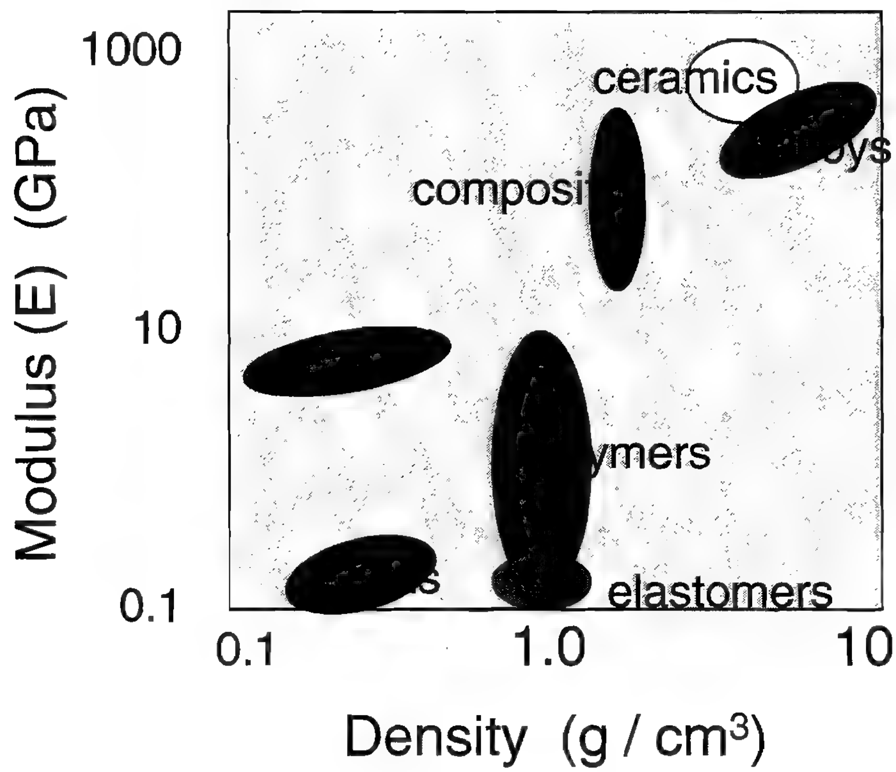
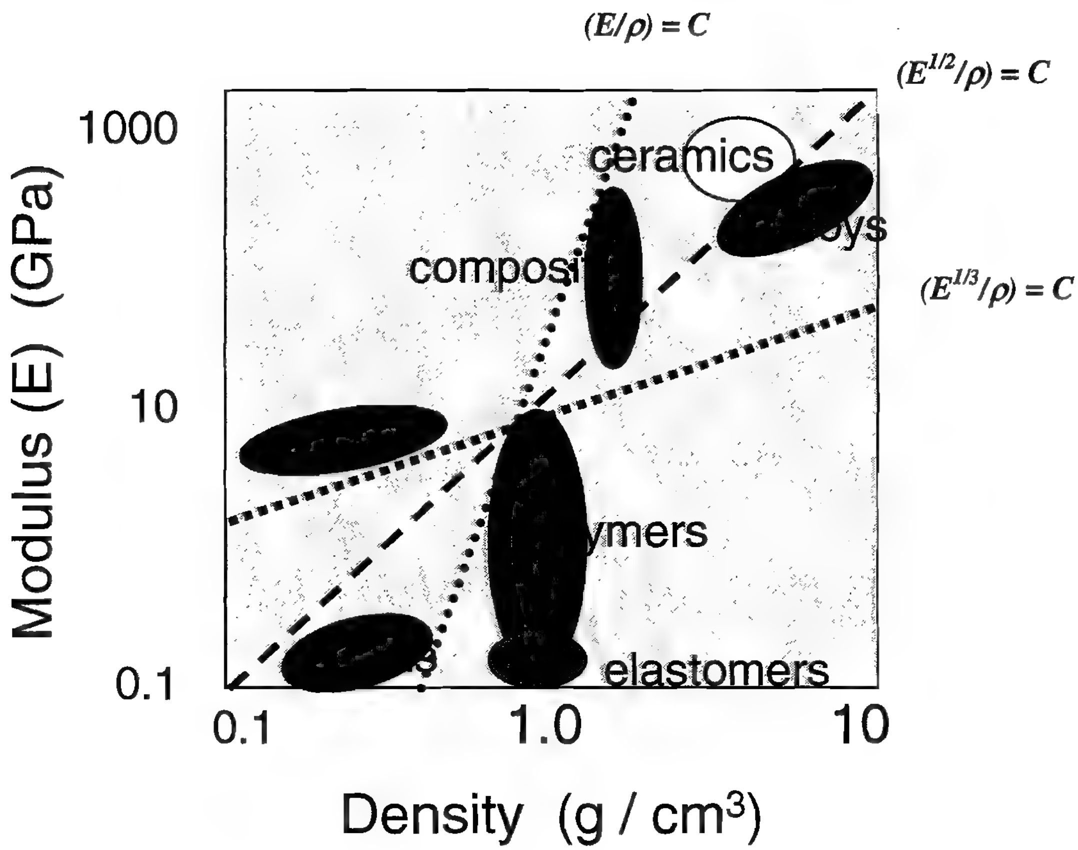


Figure 2.5: Material Class Groupings

Material performance indices are used in conjunction with sub-ranges to closely target the optimum solution. Performance indices are plots of specific functions designed from design equations (e.g. beam, column, plate equations concerning minimum weight, maximum strength, maximum stiffness, etc.). For example, when comparing Young's Modulus, E, to Density, ρ, the plotted indices represent the minimum weight design guidelines for stiff ties (tension), beams (bending), and plates (bending) as seen in Figure 2.6.



Where:

C is the Material Index constant based on Weight to Stiffness Ratio

$(E/\rho) = C$ is the minimum weight design of stiff ties
$(E^{1/2}/\rho) = C$ is the minimum weight design of stiff beams, shafts and columns
$(E^{1/3}/\rho) = C$ is the minimum weight design of stiff plates

Materials offering the greatest stiffness-to-weight ratio lie toward the upper left corner

Figure 2.6: Example of MSC with Performance Indices Plotted [13]

2.2.4 Material Selection Charts Used to Analyze Light-Weight Materials

Although there are several MSCs that compare various material characteristics, there are primarily two charts that provide general material characteristics to assist in determining the optimum material for light weight plates, beams, columns, and shafts. Cost of the

material will not be a parameter in selection at this stage due to the dynamic pricing data. The next two sections will outline each of the charts that provide general material property comparisons useful to light-weight material selection and indicate the purpose for which each is used in material selection.

2.2.4.1 Young's Modulus, E, against Density, ρ

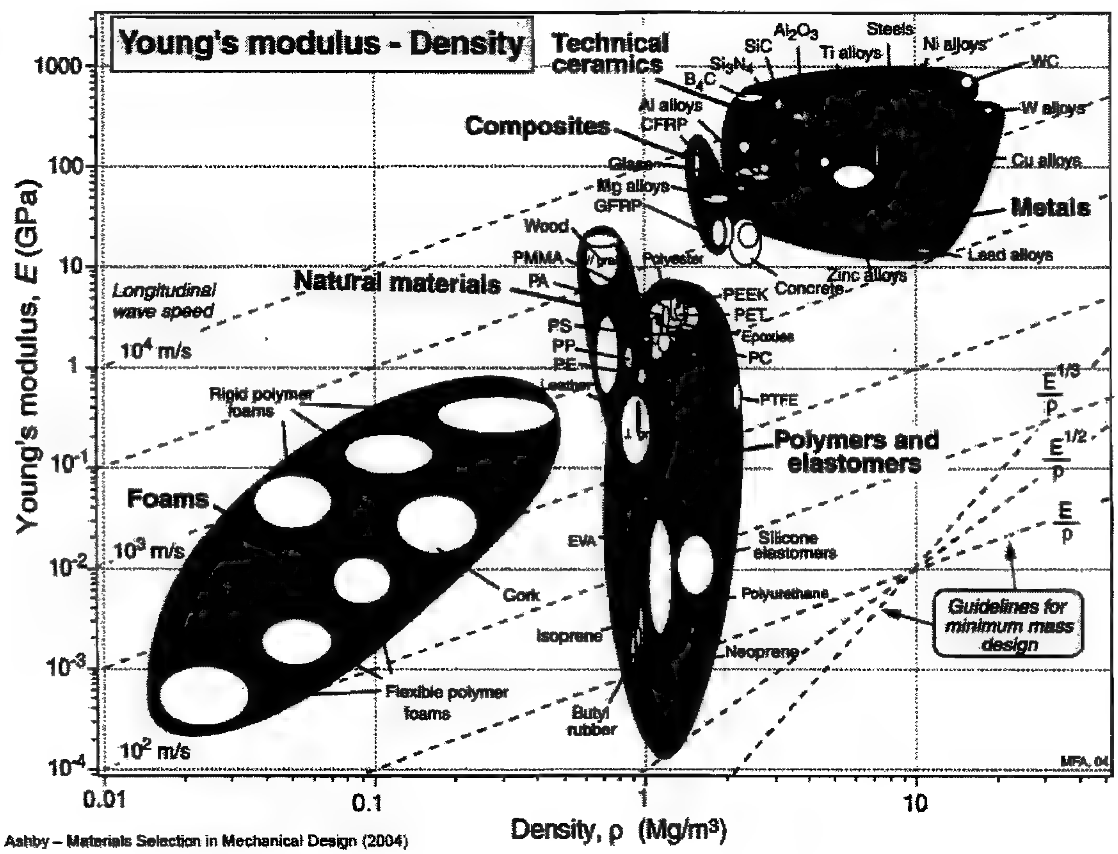


Figure 2.7: Ashby's MSC for Young's Modulus, E, against Density, ρ [13]

The chart shown in Figure 2.7 is used in the selection of materials with high stiffness and minimum weight.

The guidelines for stiff components with minimum mass are characterized by maximizing the following performance indices:

Structural Element: Ties; Minimum Deflection in Centrifugal Loading

$$M_1 = \frac{E}{\rho};$$

Structural Elements: Beams, Shafts, and Columns

$$M_2 = \frac{(E)^{1/2}}{\rho};$$

Structural Element: Plates

$$M_3 = \frac{(E)^{1/3}}{\rho};$$

Where E = Young's Modulus;
ρ = Density of Material;
M = Materials-Performance Index

2.2.4.2 Strength, σ_f, against Density, ρ

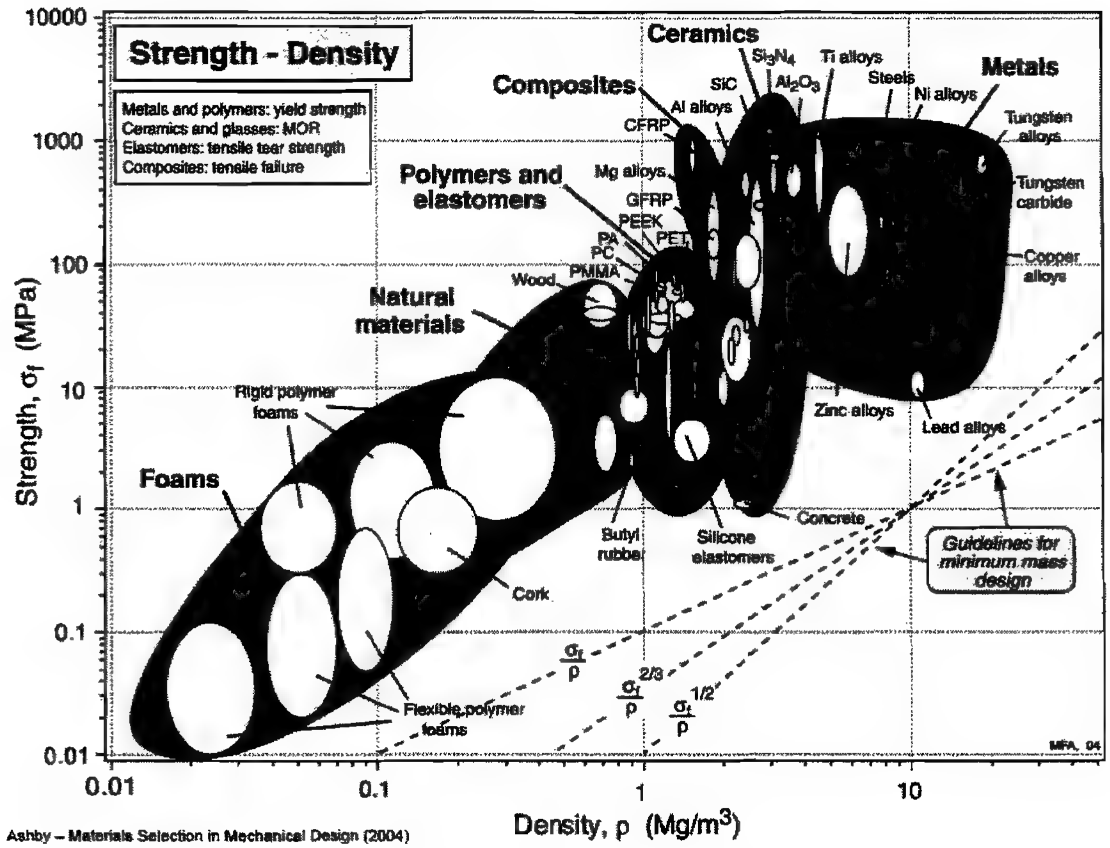


Figure 2.8: Ashby's MSC for Strength, σ_f, against Density, ρ [13]

This chart is used in the selection of materials with high strength and minimum weight. The guidelines for strong components with minimum mass are characterized by maximizing the following performance indices:

Structural Element: Ties; Minimum Deflection in Centrifugal Loading

$$M_1 = \frac{\sigma_f}{\rho};$$

Structural Elements: Beams, Shafts, and Columns

$$M_2 = \frac{(\sigma_f)^{1/2}}{\rho};$$

Structural Element: Plates

$$M_3 = \frac{(\sigma_f)^{1/3}}{\rho};$$

Where σ_f = Strength of Material;
ρ = Density of Material;
M = Materials-Performance Index

2.2.5 *Selection of Material for Ship Plating Using Ashby's MSCs*

Now, the selection process using Ashby's Material Selection Charts will be performed to find a favorable material to be used for plating on a weight critical ship when a given strength and stiffness are specified. Using the values for single skin aluminum, which is currently the most widely used material in lightweight ships, the design constraints for density, stiffness, and strength are as follows:

$$\rho_{Al} = 2.7 \text{ Mg/m}^3$$

$$\text{Young's Modulus, } E_{Al} = .209 \text{ GPa}$$

$$\text{Yield Strength, } \sigma_{f,Al} = 98.5 \text{ MPa}$$

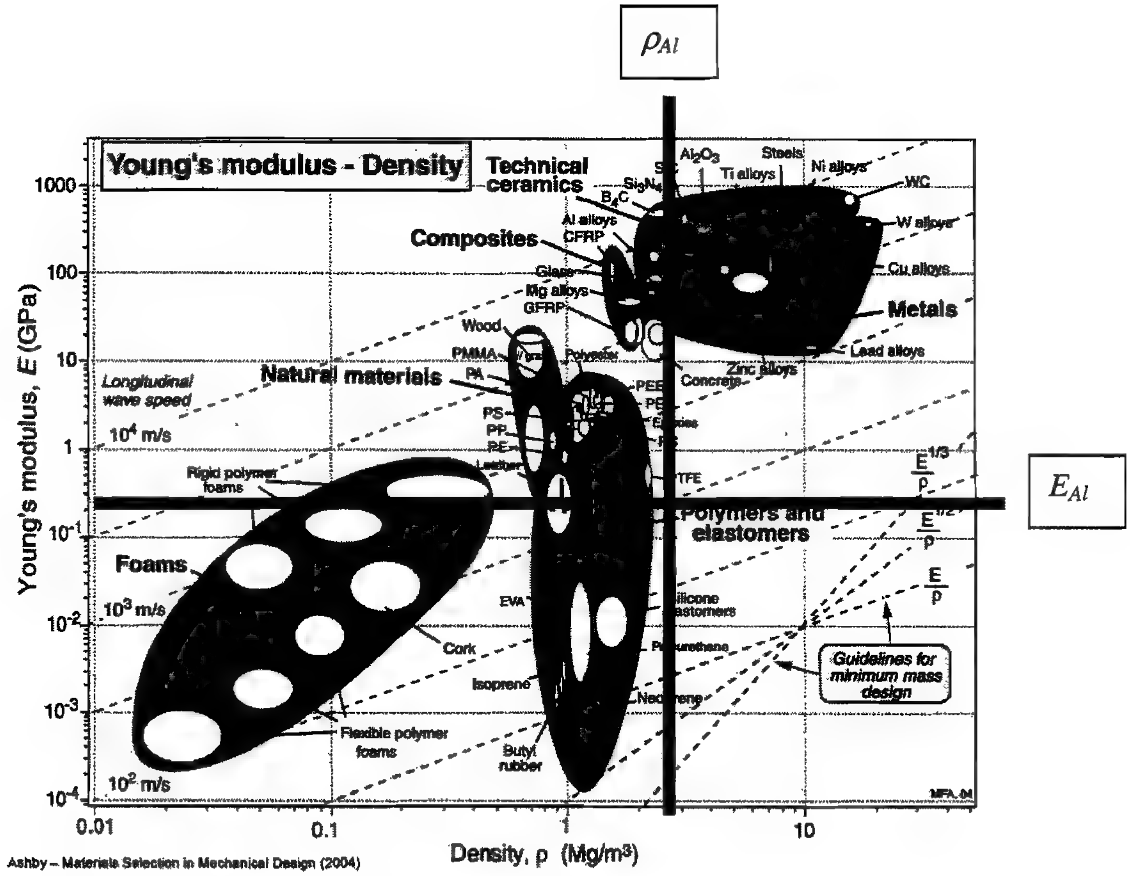


Figure 2.9: Young's Modulus, E vs. Density, ρ With Single Skin Aluminum Strength Constraint [13]

Figure 2.9 shows the plotted constraints for single skin aluminum. The objective is to maximize the following performance index:

$$M_3 = \frac{(E)^{1/3}}{\rho};$$

Based on the Young's Modulus and density constraints on the MSC, one can see that there is still a large quantity of materials that can be considered for ship plating (area enclosed by the constraints in the upper left corner.

To further narrow the materials to be considered, the strength constraint is plotted against the density.

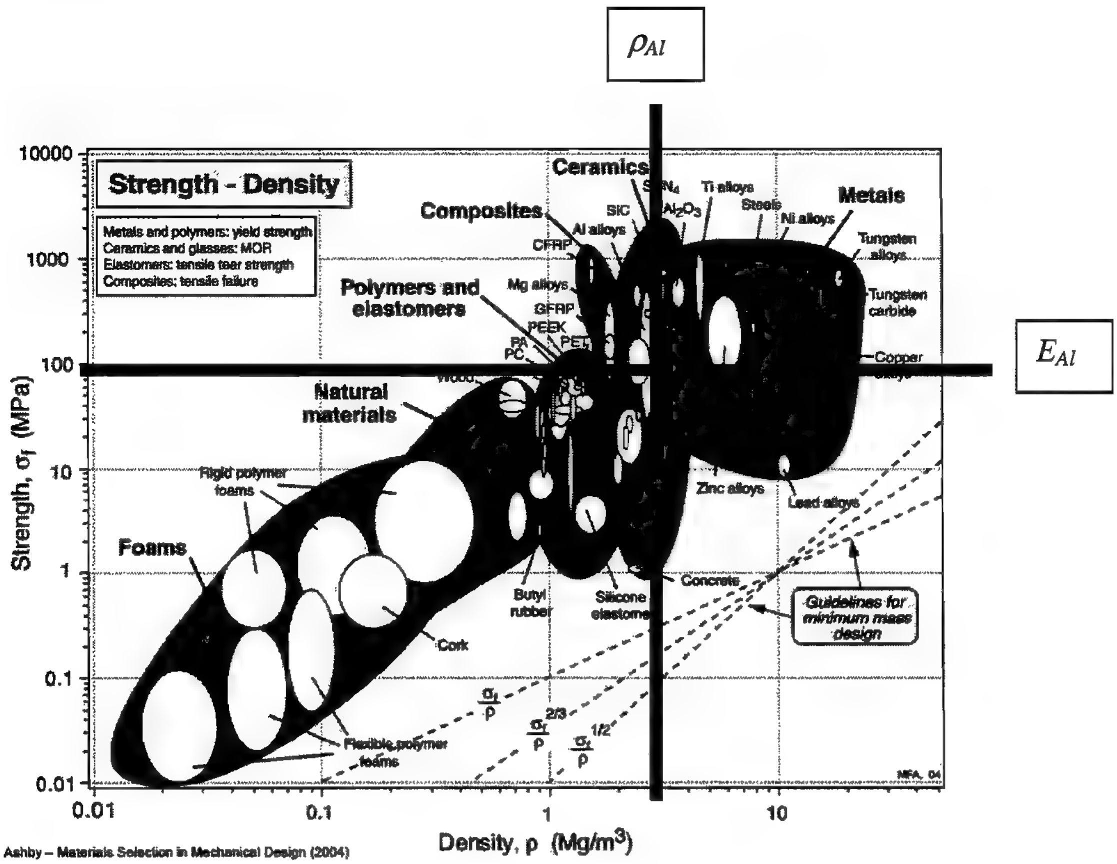


Figure 2.10: Strength, σ_f vs. Density, ρ With Single Skin Aluminum Strength Constraint [13]

Figure 2.10 demonstrates how the use of multiple MSCs can narrows the field of potential materials drastically. In this case the objective is to maximize the following performance index:

$$M_3 = \frac{(\sigma_f)^{1/3}}{\rho};$$

The strongest and lightest materials lie closest to the top left corner. Based on the strength and density constraints plotted in Figure 2.10, one can see that the top viable

material candidates for light-weight ship plating lie in the family of composite materials. In particular, CFRP has the most favorable characteristics for this application. This process demonstrates a quick yet effective way to determine an initial material or materials to be analyzed in the design process. However, it is important to note that Ashby's MSC used above do not take into account hybrid materials, multi-material structured materials, and or other non traditional materials such as ultra high performance composite concretes. In the next section a more quantitative approach will be taken to determine material selection which will allow for multi-materials and other nontraditional materials to be compared.

2.3 Multiple-Criteria Decision Making (MCDM)

2.3.1 MCDM Overview

The art of decision making and the tools used to perform simple and complex analysis have been around for centuries. As a matter of fact Benjamin Franklin was one of the first pioneers in America to develop a systematic analysis when comparing two or more alternatives. He recognized the fact that often when comparing alternatives there are multiple attributes that should be analyzed in order to make the optimum choice. By decomposing the decision into advantages and disadvantages of each option, he was able to develop a clearer picture of which choice was better then the other. It took almost two centuries later for the major development of theory and practice of decision making analysis to really take root. [14]

According to ref [15], Dr. Yazdani suggests that four primary strategies for MCDM process exist:

- Optimization
- Satisficing when optimum is not possible
- Elimination-by-aspects
- Incrementalization

First and foremost the objective is to select the best overall alternative based on the requirements for selection. When optimizing it is important to clearly identify the criteria used to evaluate the alternatives. When possible, express the criteria in mathematical terms so that the results can be more easily validated and expressed in term quantitative expressions. When qualitative data is part of the criteria subset, convert the data to a quantity consistent with the qualitative value to ensure an apples-to-apples comparison is being conducted. Optimizing essentially picks the alternative with the highest number of positive attributes while minimizing the number of negative attributes.[15]

Satisficing, which is a word coined by an American political scientist, Herbert Simon, means a behavior which attempts to achieve at least some minimal level, but which does not necessarily maximize its value.[14] When the optimal is not required or possible, satisficing is used in order to pick the best solution that meets the minimum requirements. It is paramount to prioritize desired attributes and start with the most important one. This is primarily used not necessarily to maximize but to meet desired constraints.[15]

The elimination-by-aspects is self evident. Basically, the goal here is to eliminate alternatives that fail to meet a requirement. An aspect is virtually a constraint with one or

more criteria. Ordering of aspects can have a very large effect on the outcome because an otherwise excellent alternative can be eliminated because of its failure to meet the minimum requirement in any one category. A comparison of all attributes of each alternative with all criteria must be conducted to ensure a valid solution and prevent ambiguity between alternatives that may have the same number of positive and negative qualities.[15]

The strategy of incrementalization is to provide a baseline of the current alternative and compare the proposed alternatives to it. In this case, the decision maker is intending to improve the level of desired outcome in making the decision without diminishing the current attributes.[15]

Although there are several different major classes of MCDM methods that can be used for analysis, however Figure 2.11 provides a flowchart of the basic MCDM process.

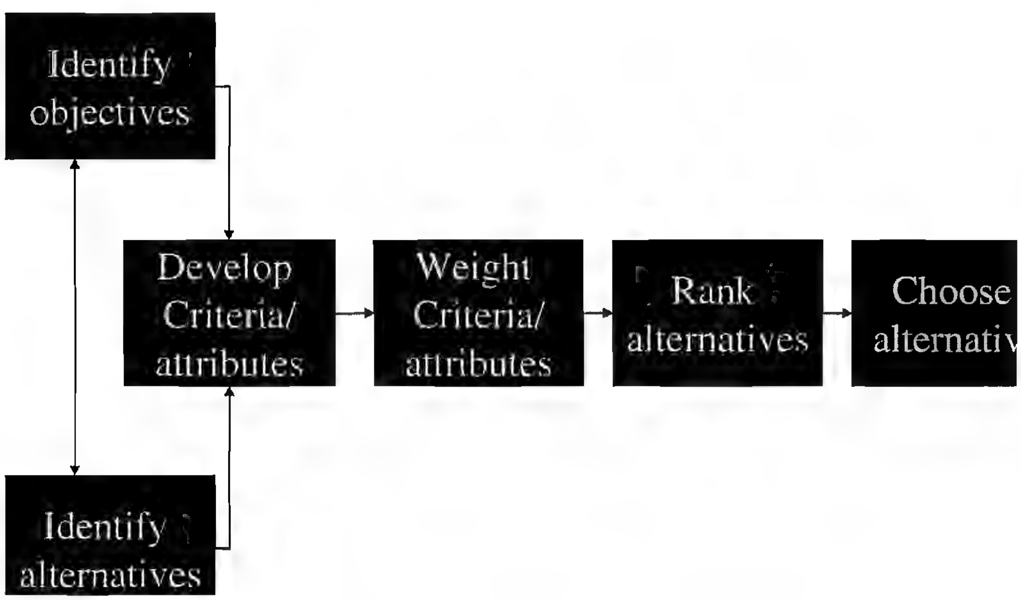


Figure 2.11: Generic Multi-Criteria Decision Process [15]

In the case for the selection of light-weight materials for high speed craft, there are multiple attributes that must be compared between the various alternatives of materials. Thus, a Multiple Attribute Decision Matrix (MADM) will be used. Although there are many types of MADM methods based on weighting procedures and given data, a decision matrix for multiple attributes can be described as a matrix that compares the attributes of each alternative with one another. Based on the weighting scheme which will be more clearly defined in the next section, an optimal alternative can be determined by comparing each attribute with the criteria after applying a preference weight based on the designer's performance requirements.

Alternatives

	X_1	X_2	X_3				X_n
A_1	v11	v12	v13				v1n
A_2	v21	v22	v23				v2n
A_3	v31	v32	v33				v3n
A_m	vm1	vm2	vm3				vmn

Figure 2.12: MADM Matrix [15]

Figure 2.12 shows a typical MADM matrix with values of v_{ij}, which indicate the performance value of alternative A_i when it is evaluated in terms of attribute X_j.

Once the materials attribute values are obtained then normalization of the performance values occurs regardless of the type of data used in determining the values (i.e. stochastic, deterministic, or fuzzy). The performance values can be normalized linearly or non-

linearly depending on the scope and complexity of desired results. The figure on the next page shows the normalized MADM matrix and the associated equations for normalization depending on the desired characteristics of the respective attributes.

Attributes

Alternatives

	X1	X2	X3				Xn
A1	r11	r12	r13				r1n
A2	r21	r22	r23				r2n
A3	r31	r32	r33				r3n
Am	rm1	rm2	rm3				rmn

For positive attributes
Where more is better

$$r_{ij} = \frac{V_{ij} - \min\limits_{j} V_{ij}}{\max\limits_{j} V_{ij} - \min\limits_{j} V_{ij}}$$

For negative attributes
Where less is better

$$r_{ij} = \frac{\max\limits_{j} V_{ij} - V_{ij}}{\max\limits_{j} V_{ij} - \min\limits_{j} V_{ij}}$$

Figure 2.13 Normalized MADM Matrix [14]

Where values of r_{ij} represent the normalized value of alternative A_i when it is evaluated in terms of attribute X_j.

2.3.2 Modified Digital Logic (MDL) Method

The MDL method is a relatively new method that has been proposed by B. Dehgham-Manshadi et al. in ref [17]. It is a decision making method created from the more commonly used Weighted Product Model (WPM) method in which each alternative is compared with the others by multiplying a ratio of the scaled values to a weighted factor, α to each criterion. The weighted factors are based on the designer's priority on selection criterion. The series of multiplication allows for dimensionless analysis where relative values instead of actual values are used. The WPM method as well as the Modified Digital Logic (MDL) method can be used when multiple properties, such as those in material selection analysis, are to be considered. However, the disadvantage of the WPM is that where there is a large variance in attributes and the significance of each is ambiguous, determination of the weighting factors can cause error and/or unreliable selection.[17] The difference between the WPM and the Digital Logic Method is how the alternatives are evaluated. The Digital Logic Method provides a more quantitative approach to solving for the weighting factor, α, thus eliminating the potential for guesswork and creating a more reliable approach to optimum choice selection. In WPM, all the alternatives are given an assigned weight and are evaluated at once, while the Digital Logic Method only evaluates two alternatives at a time.[17] In the case of material selection, every material property and characteristic is evaluated against each other and a binary score of zero (0) or one (1) is assigned based on which is less important and which is more important respectively. Basically, for each attribute of each material the question asked is, which one is more important for the desired outcome of the end product, property A or property B? After each combination is compared and

assigned a binary score, the results are put into a matrix and a weighting factor, α for each property is calculated by dividing the ratio of its respective sum of ones (positive decisions) over the total number of possible decisions, N.

$$N = \frac{n(n-1)}{2}; \qquad (2.1)$$

$$\sum \alpha = 1; \qquad (2.2)$$

Where n is the number of properties or goals under consideration. The summation of the weighting factors equal unity. Then each value of each property are scaled and multiplied by the weighting factor to get a performance index, γ, for each material. The materials can then be ranked and the material with the highest performance index is the material of choice.

The Digital Logic Method has to be modified because of some flaws in the scaling procedure. If a property or goal under consideration is always ranked last it is given a zero weighted factor and thus has no effect on the outcome. Also, there was no way to account for equal weighted properties. So, the Digital Logic Method is modified to account for these shortcomings by making the scale of scores for the weighted factors one (1) least important, two (2) for when the properties are equal, and three (3) for the most important.[17] This change allows even the lowest priority properties to be considered in the selection and also allows for equal weights to be assigned to equally important properties.[17] An assessment of specifically how the weighting assignments will be prioritized for the selection of light-weight materials for use on weight critical ships will be examined in the next section.

2.4 Light-Weight Material Selection Using MDL Method

2.4.1 Weighting Assignments of Material Factors for Weight Critical Ships

After the various materials have been identified for potential candidates for selection, the first step in the assessment of weighting assignments is to clearly define the performance requirements of the system to be designed. In this case, the system is a light-weight high-speed vessel. In particular, the material selection is sought for the structural components of the ship such as hull plating, superstructure panels, decks, and beams. The salient material properties are then identified and ranked in order of precedence based on the desired characteristics of the ship's design. As with most mechanical systems, when selecting a material to be used in the construction of a light-weight craft emphasis is placed on strength, stiffness, general fabrication costs, and in this case largely on weight. Based on research and discussion with material experts at NAVSEA and in the naval light-weight craft industry, a table of general material requirements was generated and is shown in Table 2.1. It is important to note that the qualitative values are based on the author's research and may be open to other interpretations.

Attributes

Material	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Grade A Steel	34	29600.00	High	Very High	Low	Avg	Low	7.8	None
Single Skin Aluminum (A5086-H34)	20	10000.00	Low	High	High	Low	Avg	2.7	High
Aluminum Sandwich (honeycomb core)	39	10000.00	Avg	Avg	High	Avg	Avg	1.8	Very High
LASCOR Steel	55	29600.00	High	Avg	High	Very High	High	5.2	High
Composite (CFRP) Carbon w/ Vinyl Ester Resin	217	33000.00	Low	Avg	Very High	Very High	Avg	1.8	Very High
DUCTAL (UHP2C) *	32	7820.00	Very High	Very High	Very High	Very Low	Very High	2.5	High

Table 2.1: Properties for Material Candidates for Weight Critical Ships

Where the given attributes are:

(1) Yield Strength (ksi)

(2) Young's Modulus (ksi)

(3) Fire Resistance

(4) Repairability

(5) Resistance to Corrosion

(6) Fabrication Cost

(7) Risk

(8) Mass Density (g/cm3), ρ

(9) Overall Potential For Weight Savings

With the exception of the ultra high performance concrete composite, the materials in Table 2.1 were selected based on the Navy's current construction practices and advanced materials research in the area of light-weight construction.[4] The table above shows several qualitative rankings for various attributes and those values must be converted to quantitative values in order to be compared to the other values. Using Rao's fuzzy score conversion scale [ref 18], qualitative values can be easily converted to quantitative values. Table 2.2 below shows the assigned quantitative value based on the fuzzy conversion scale.

Material	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Grade A Steel	34	29600.00	0.665	0.745	0.335	0.500	0.335	7.8	0.000
Single Skin Aluminum (A5086-H34)	20	10000.00	0.335	0.665	0.665	0.335	0.500	2.7	0.665
Aluminum Sandwich (honeycomb core)	39	10000.00	0.500	0.500	0.665	0.500	0.500	1.8	0.745
LASCOR Steel	55	29600.00	0.665	0.500	0.665	0.745	0.665	5.2	0.665
Composite (CFRP) Carbon w/ Vinyl Ester Resin	217	33000.00	0.335	0.500	0.745	0.745	0.500	1.8	0.745
DUCTAL (HP2C) *	32	7820.00	0.745	0.745	0.745	0.255	0.745	2.5	0.665

Table 2.2: Quantitative Values for Material Properties Using Rao's Fuzzy Conversion Scale

Traditionally, naval ships that are not weight critical are constructed from Grade A steel of varying strengths depending on the structural requirements. Although Grade A steel is not typically used in light weight construction due to the weight restrictions, it has been

included in the table to show a baseline for the comparison of materials. Although the naval construction industry is increasing using many different types and combinations of materials to reduce topside and overall weight, the primary light-weight material used in construction up to this point has been single skin aluminum. Single skin aluminum is one third the weight of steel, it is relatively inexpensive as a raw material, and has excellent anti-corrosion characteristics. However, its strength, stiffness, hull flexibility, fire resistance are concerns and new materials have vastly improved characteristics with the same or more weight savings. New materials fabrication processes and geometries have shown promise for use in weight critical ship application. Materials such as light-weight aluminum and steel sandwich materials, composites, and even non-traditional materials such as ultra high performance concrete composite must be considered if the search for the optimum material is desired for a given application.

Now that the proposed materials and their respective properties for comparison have been identified it is time to conduct the MDL method to compare each material attribute with each other to determine an order of importance to obtain the weighted assignments. Given the nine goals of design for light-weight material selection, there are thirty-six possible decisions to make when comparing the attributes two at a time.

The scaled ranking consists of the following:

Rank of one (1) = Least important

Rank of two (2) = Attributes are equal (one is not better or worse than the other)

Rank of three (3) = Most important

The next three tables show the rankings of the thirty six decision points.

Number of Possible Decisions (1-15)

Goals	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Yield Strength	3	3	3	3	2	3	1	1							
Young's Modulus	1								3	3	3	2	3	1	1
Fire Resistance		1							1						
Repairability			1							1					
Resistance to Corrosion				1							1				
Fabrication Cost					2							2			
Risk						1							1		
Mass Density, ρ							3							3	
Overall Potential For Weight Savings								3							3

Table 2.3: Modified Digital Logic Method (Decision Points 1-15)

Number of Possible Decisions (16-30)

Goals	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Fire Resistance	1	3	1	3	1	1									
Repairability	3						1	1	2	1	1				
Resistance to Corrosion		1					3					1	1	1	1
Fabrication Cost			3					3				3			
Risk				1					2				3		
Mass Density, ρ					3					3				3	
Overall Potential For Weight Savings						3					3				3

Table 2.4: Modified Digital Logic Method (Decision Points 16-30)

Number of Possible Decisions (31-36)

Goals	31	32	33	34	35	36
Fabrication Cost	3	1	1			
Risk	1			1	1	
Mass Density, ρ		3		3		1
Overall Potential For Weight Savings			3		3	3

Table 2.5: Modified Digital Logic Method (Decision Points 31-36)

The weighting factors, α, are found by dividing the number of positive decisions for each attribute over the total number of positive decisions in the matrix, N. The results of this table reflect the designer's desired characteristics for the optimal material solution.

Material Attribute	Positive Decisions	Weighting Factors, α
Yield Strength	19	0.158
Young's Modulus	17	0.142
Fire Resistance	12	0.100
Repairability	11	0.092
Resistance to Corrosion	10	0.083
Fabrication Costs	18	0.150
Risk	11	0.092
Mass Density	22	0.183

Table 2.6: Attribute Weighting Factors

When considering non-linear normalization, in order to more finely tune the material selection to the designers desired parameters, a critical value, X_c is assigned. The critical value for each attribute for which a property is less than becomes negative thus reducing the performance index for that parameter. Table 2.7 below shows the assigned critical value. Non-linear normalization is covered in detail in the next section.

Material Attribute	**Critical Value, X_c**
Yield Strength (ksi)	34
Young's Modulus (ksi)	10,000
Fire Resistance	0.335
Repairability	0.665
Resistance to Corrosion	0.665
Fabrication Costs	0.335
Risk	0.335
Mass Density (g/cm^3)	2.7

Table 2.7: Critical Values, X_c

In the case of this study, the most common light-weight material property values were used (single skin aluminum) to ensure that the material selected was as good as or better than the current industry standard. The next section will show how linear and non-linear normalization affects the results of the material selection and which is better for the case of selecting the best light-weight material for high-speed craft applications.

2.4.2 Linear and Non-linear Normalization

As mentioned in the previous section, WPM and MDL both use a weighted property value to determine the ranking and optimum selection. The weighted property or performance index, γ, for each material is obtained by summing the product of the scaled property values, Y, and the property weighting factors, α.

$$\gamma = \sum_{i=1}^{n} Y_i \alpha_i ; \quad (2.3)$$

Where i is summed over all the relevant material properties.[17]

Traditionally, WPM methods use linear normalization, however both linear and non-linear normalization of the material property values in Table 2.2 will be used to conduct the MDL method analysis for light-weight material selection in order to gain a better understanding of how the non-linear analysis and critical factor, X_c from Table 2.7 influence the final outcome.

The linear normalization consists of a simple linear function that yields scaled properties, Y, between zero (0) and one hundred (100).[17] The best value receives a 100 and the remaining values are scaled proportionally.

The general equations for linear normalization are as follows:

When highest value is most desirable:

$$Y = \frac{X}{X_{\max}} * 100 ; \qquad (2.4)$$

Where: X = numerical value of given property for the material

X_{max} = overall maximum value for that property

When lowest value is most desirable:

$$Y = \frac{X_{\min}}{X} * 100 ; \qquad (2.5)$$

Where: X = numerical value of given property for the material

X_{min} = overall minimum value for that property

The proposed MDL method in ref [17] uses non-linear normalization vice linear normalization to achieve "more reasonable" results by maintaining a more balanced assessment and not over emphasizing any of the high and low extremes. However, Rao ref [18] suggests that the use of the non-linear approach and the critical value, X_c, allows more influence from the designer.

The equations for non-linear normalization of the material property values are as follows:

When highest value is most desirable:

Boundary Conditions: $Y = -100$ at $X = 0$; $Y = +100$ at $X = X_{\max}$; $Y = 0$ at $X = X_c$;

$$a_1 = \frac{-100}{\ln\left(\dfrac{X_c}{X_{\max} - X_c}\right)}; \text{ (2.6)}$$

$$b_1 = \frac{X_{\max} - 2X_c}{X_c(X_{\max} - X_c)}; \text{ (2.7)}$$

$$c_1 = \frac{X_x}{X_{\max} - X_c}; \qquad \text{(2.8)}$$

$$Y = a_1 \ln(b_1 X + c_1) \text{ for } X_c \neq X_{\max}/2; \qquad \text{(2.9)}$$

$$Y = \frac{200X}{X_{\max}} - 100 \text{ for } X_c = X_{\max}/2; \qquad \text{(2.10)}$$

Where: X = numerical value of given property for the material

X_{max} = overall maximum value for that property

X_c = critical value designated by expert

a_1, b_1, c_1 = constraints

When lowest value is most desirable:

Boundary Conditions: $Y = +100$ at $X = X_{\min}$; $Y = -100$ at $X \to +\infty$; $Y = 0$ at $X = X_c$;

$$a_2 = \frac{-100}{\ln\left(\dfrac{-X_{\min}}{X_{\min} - X_c}\right)} \quad ; \qquad (2.11)$$

$$b_2 = \frac{-X_c^2 + 2X_{\min} X_c}{X_{\min} - X_c} \quad ; \qquad (2.12)$$

$$c_2 = \frac{-X_{\min}}{X_{\min} - X_c} \quad ; \qquad (2.13)$$

$$Y = a_2 \ln(\frac{b_2}{X} + c_2) \text{ for } X_c \neq 2X_{\min}; \quad (2.14)$$

$$Y = \frac{200X_{\min}}{X} - 100 \text{ for } X_c = 2X_{\min}; \qquad (2.15)$$

Where: X = numerical value of given property for the material

X_{min} = overall minimum value for that property

X_c = critical value designated by expert

a_2, b_2, c_2 = constraints

When substituting the corresponding constraints into the necessary scaled value equations and then multiplying the results by the attribute weighting factors in Table 2.6, the performance indices from Eqn. 2.3 can be solved and the materials can be ranked.

2.4.3 Selection of Materials Based on Properties

Now, the steps of the MDL method are put together to solve for the optimum light-weight material based on the properties in Table 2.2. It is important to realize that the material selected by this process at this stage may not be the best material for the intended application. Further analysis such as structural and conditional loading test must be done to ensure the material is appropriately matched for its intended use in the high-speed craft. The structural and loading analysis will be undertaken in the next step and will be examined closely in the next chapter. The MDL selection process will be conducted using both linear and non-linear normalizations of the properties in order to better understand the sensitivity of the each property attribute and associated weighting factors to the final material rankings.

Using Eqns. (2.4) and (2.5) for linear normalizations and Eqns. (2.9) and (2.10) for non-linear normalizations, the following normalized material properties are given for the non normalized values in Table 2.2:

Attributes

Material	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**
Grade A Steel	15.67	89.70	89.26	100.00	44.97	51.00	100.00	23.08	0.00
Single Skin Aluminum (A5086-H34)	9.22	30.30	44.97	89.26	89.26	76.12	67.00	66.67	89.26
Aluminum Sandwich (honeycomb core)	17.97	30.30	67.11	67.11	89.26	51.00	67.00	100.00	100.00
LASCOR Steel	25.35	89.70	89.26	67.11	89.26	34.23	50.38	34.62	89.26
Composite (CFRP) Carbon w/ Vinyl Ester Resin	100.00	100.00	44.97	67.11	100.00	34.23	67.00	100.00	100.00
DUCTAL (UHP2C) *	14.75	23.70	100.00	100.00	100.00	100.00	44.97	72.00	89.26

Table 2.8: Linear Normalization of Material Properties

Attributes

Material	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Grade A Steel	21.33	89.52	82.01	100.00	-72.35	-46.88	100.00	-72.58	-100.00
Single Skin Aluminum (A5086-H34)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Aluminum Sandwich (honeycomb core)	26.98	0.00	42.70	-48.86	0.00	-46.88	0.00	100.00	100.00
LASCOR Steel	41.30	89.52	82.01	-48.86	0.00	-68.17	-32.14	-56.63	0.00
Composite (CFRP) Carbon w/ Vinyl Ester Resin	100.00	100.00	0.00	-48.86	100.00	-68.17	0.00	100.00	100.00
DUCTAL (UHP2C) *	18.85	-15.79	100.00	100.00	100.00	100.00	-41.20	12.03	0.00

Table 2.9: Non-linear Normalization of Material Properties

Where once again the attributes are:

(1) Yield Strength (ksi)

(2) Young's Modulus (ksi)

(3) Fire Resistance

(4) Repairability

(5) Resistance to Corrosion

(6) Fabrication Cost

(7) Risk

(8) Mass Density (g/cm3), ρ

(9) Overall Potential For Weight Savings

Other than the obvious differences in how the two approaches are calculated, the main differences in the normalized scaled property values is that the results from the non-linear method provide a wider range values between the material properties and also include both negative and positive values. This can be attributed to the boundary conditions where the scaled values, Y, center upon a design critical value, X_c set forth in Table 2.7. As ref [15] suggests, the resultant scaled values are more evenly dispersed and larger numerical difference can be seen between each material. Thus, based on Eqn. (2.3) the performance indices, γ, will show a more distinct ranking priority between the materials as seen in the ranking summary table that follows.

Material	*Performance Index, γ	*Rank	**Performance Index, γ	**Rank
Grade A Steel	58.08	6	-3.77	6
Single Skin Aluminum (A5086-H34)	73.50	4	0.00	4
Aluminum Sandwich (honeycomb core)	79.57	3	35.36	3
LASCOR Steel	73.19	5	-0.61	5
Composite (CFRP) Carbon w/ Vinyl Ester Resin	98.59	1	61.96	1
DUCTAL (UHP2C) *	83.37	2	41.68	2

* Calculated using linear normalization
** Calculated using non-linear normalization

Table 2.10: Material Rankings Based on Properties Using MDL method

In this case, the material rankings are the same both linear and non linear normalizations and both rank CFRP with vinyl ester resin as the best all around choice. As expected, due to the light-weight ship criteria set forth in the weighting factors, α, from Table 2.6, Grade A steel, which is the heaviest material, placed last. However, it was not evident which material would rise above the rest when compared to another material with differing strengths and weaknesses. For example, even though the overall objective was

to select the strongest and lightest material, a definite decision could not be made by comparing only the aforementioned attributes and neglecting the others because they were less important. Each attribute contributes to the overall selection and can make the difference in its final rank against the other materials. Table 2.11 shows how none of the materials examined dominated or was dominated by all attributes. As a matter of fact, each material was the best and/or the worst of at least one or more attributes. For example, CFRP was the best in five attributes but worst in three, yet still was ranked the best overall, while Grade A steel was best in two attributes and worst in three, yet was ranked last. Thus, the MDL method is proven to show optimization potential for selections between several light-weight materials where the apparent "best" decision is not obvious and how the final rankings are influenced by the designer's desired material performance requirements.

Property	Best Material(s)	Worst Material(s)
Yield Strength	CFRP (217 Ksi)	Single Skin Al. (20 Ksi)
Young's Modulus	CFRP (33,000 Ksi)	DUCTAL (7820 Ksi)
Fire Resistance	DUCTAL (Very High)	Single Skin Al. (Low) CFRP (Low)
Repairability	DUCTAL (Very High) Grade A Steel (Very High)	Al. LMS w/honeycomb Core (Avg) CFRP (Avg) LASCOR (Avg)
Resistance to Corrosion	CFRP (High) DUCTAL (High)	Grade A Steel (Low)
Fabrication Costs	DUCTAL (Low)	LASCOR (Very High) CFRP (Very High)
Risk	Grade A Steel (Low)	DUCTAL (Very High)
Mass Density	CFRP (1.6)	Grade A Steel (7.8)
Overall Potential for Weight Savings	Al. LMS w/honeycomb Core (Very High) CFRP (Very High)	Grade A Steel (None)

Table 2.11: Best and Worst Material(s) Based on MDL Rankings

Also, intuitively the wide dispersion of ranking values in the non-linear approach demonstrate how the designer's influence can have a large effect on the resultant outcome based on preference and weight assigned to a certain attribute. Surprisingly, a non-traditional material, (UHP2C) DUCTAL ©, is shown to have potential for application on weight critical ships. This process demonstrates how existing materials as well as new materials can be compared and initially assessed for optimum design. The next step is to provide more detail in the analysis of material selection by exploring actual plate buckling criteria in terms of uni-axial compression.

Chapter 3. Material Selection Based on Buckling Criteria for Uni-Axial Compression

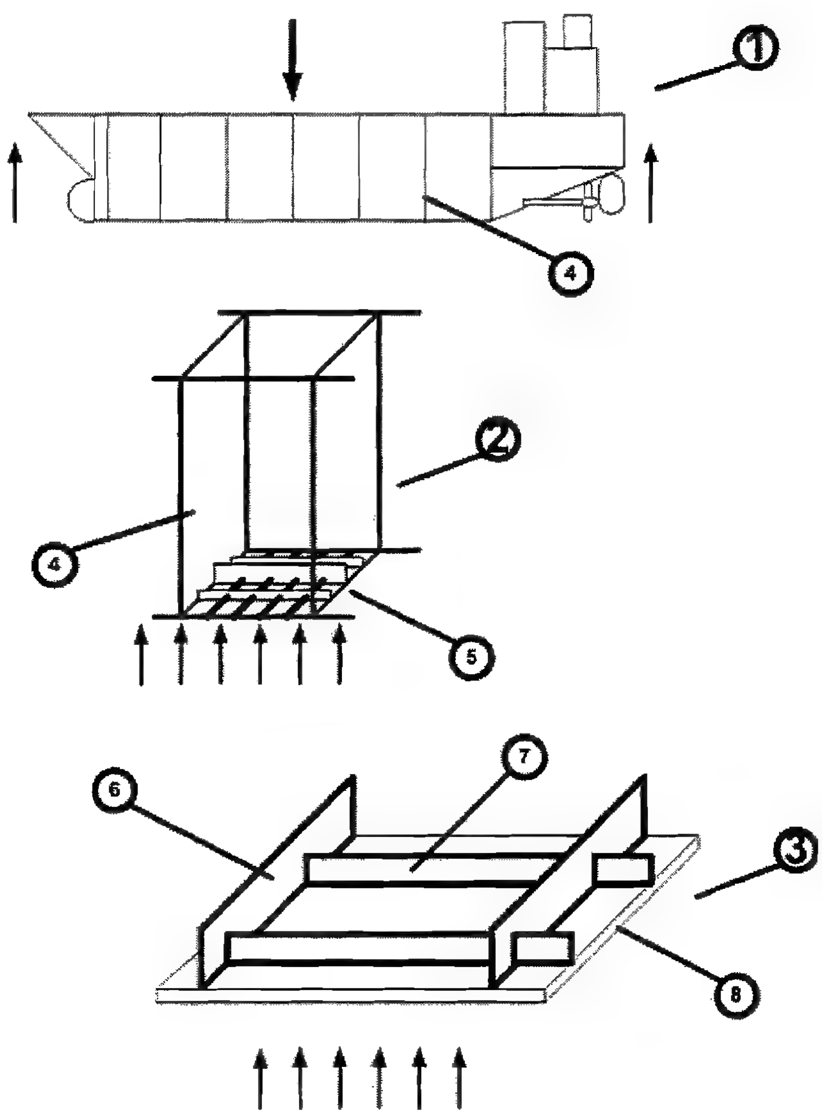
3.1 Introduction

As with any beamlike structure, a ship in water is subjected to loads that cause stresses and strains. Even in an ideal situation, in which the ship's structure, equipment and cargo are evenly distributed along the entire length of the ship with the buoyant force, stresses and strains still exist on the hull due to environmental forces such as wind, water pressure, etc. Thus, loading analysis is paramount in the material selection process. Load induced stresses on ships can be broken down into three groups [22]:

Group	**Area Affected**
Primary	Structural, hull girder
Secondary	Local, major substructures, hull, bulkheads
Tertiary	Very localized, small areas of plating, single stiffeners

Table 3.1: Stress Groups on Ships [22]

Figure 3.1 shows a representation of how each group of stresses affect the hull and interior structure in terms of deflection. Total stress on the ship at any given point is the result of summing all three groups of stresses. [22]



Primary (1), Secondary (2), Tertiary (3), Watertight bulkheads (4), Ship's hull bottom structure including keel, keelsons, and transverse frames between two bulkheads (5) Transverse frames (6), Longitudinal stiffeners (7), Hull plating (8)

Figure 3.1: Representations of Stress Deflections on Ship Structures [23]

When considering the ship as a beam-like structure, the primary stresses flex and twist the hull. Hull flexing in the lateral plane is caused by an uneven distribution of the weight of the ship and its buoyant forces. These stresses cause deflections that are called hogging and sagging. Hogging is when the bending moment causes the center of the ship's hull in the longitudinal direction to bend upward creating compression on the keel or bottom of the ship and tension on the upper decks. Sagging is when the buoyant forces create a bending moment that causes the center of the ship's hull in the longitudinal direction to bend downward creating tension of the bottom of the ship and compression on the upper decks. Figure 3.2 below shows primary bending deflections in the lateral plane (sagging (1) and hogging (2)).

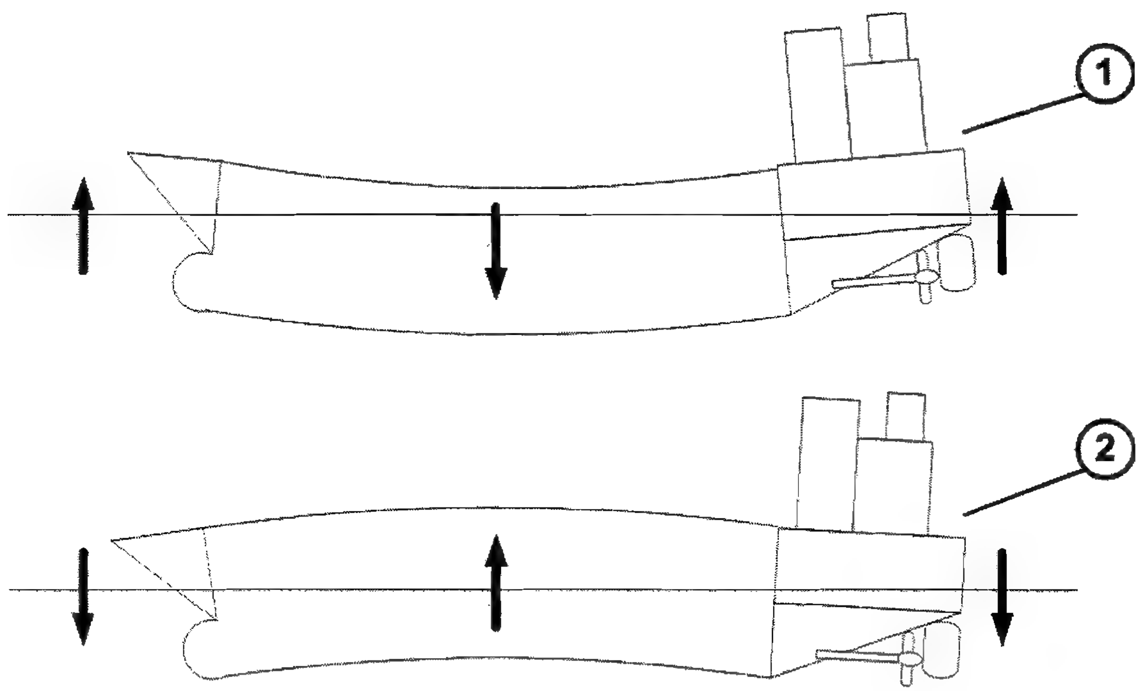


Figure 3.2: Lateral Bending Deflections [23]

Torsional twisting is caused when there is a traverse induced force on the hull. On a vessel transverse plane loading can be caused by the rolling of the ship from side to side and or waves that meet the ship's hull at oblique or perpendicular to the ship's hull. The intensity of bending moment is proportional to the square of the length of the vessel.[4]

As mentioned earlier, secondary stresses affect local areas of the structure. Ship speed, sea state, and hull geometry are all key factors in the intensity of secondary stresses. They are created by static and dynamic forces that include the following:

- Hydrodynamic Pressure – caused by hydrodynamic interactions with hull
- Slamming – caused by the bow pitching in heavy seas and impacting the water
- Wave Slapping – caused by waves impacting hulls sides and transom
- Green Sea Loads – caused by excessive waves that crash into deckhouse and superstructure

3.2 Buckling Criteria: Uni-Axial Compressive Stress

Due to the complexity of ship design and the vast number of different shapes and sizes of ship structural components, it is not the aim of this thesis to specifically analyze any given component or the ship structure as a whole. The combined ship structure and even specific structural component analysis requires targeted research and evaluation which is beyond the scope of this thesis. Rather it is the intended purpose of this evaluation to apply the MDL method to compare each of the materials strictly in terms of cost and weight. In order to get a similar comparison, the first step is to calculate the required plate thicknesses to achieve the same ideal elastic compressive strength.

For ships, uni-axial compression is evaluated in two ways: plates with longitudinal framing and plates with transverse framing. The figures below demonstrate graphically the orientation of the forces applied.

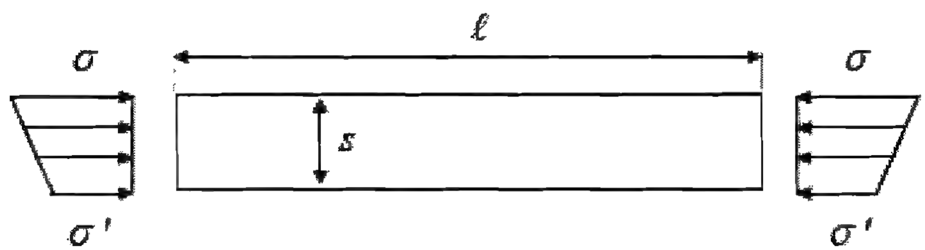


Figure 3.3: Plate with Longitudinal Framing [3]

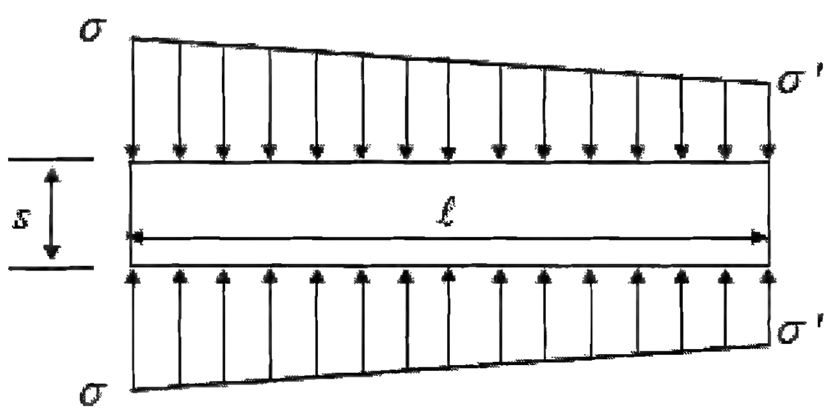


Figure 3.4: Plate with Transverse Framing [3]

Where σ equals σ' and the plates length, *l*, is greater or equal to the short side, *s* for both cases.

The ideal elastic stress for plates in uni-axial compression can be calculated using the following equation:

$$\sigma_E = \overline{K}E(\frac{t_b}{s})^2 \qquad (3.1)$$

Where: $\overline{K} = \dfrac{\pi^2 m_1}{12(1-\upsilon^2)}$

m_1 = Buckling coefficient

E = Modulus of Elasticity (N/mm^2)

t_b = Thickness of plating (mm)

s = Shorter side of plate panel (mm)

Although the Poisson's ratio, ν, values slightly differ between the various materials, the differences are insignificant in the calculation for $\overline{K}$. Thus, a value of $\nu = .3$ is assumed for all materials and the following ref [3] equation is sufficient for this study of ideal elastic stress for plates in uni-axial compression:

$$\sigma_E = 0.9 m_1 E(\frac{t_b}{s})^2 ; \qquad (3.2)$$

The critical buckling stress can then be calculated using the following equations:

$$\sigma_C = \sigma_E \quad \text{when} \quad \sigma_E \leq 0.5\sigma_y ; \qquad (3.3)$$

$$\sigma_C = \sigma_y(1 - \frac{\sigma_y}{4\sigma_E}) \quad \text{when} \quad \sigma_E > 0.5\sigma_y ; \qquad (3.4)$$

Where: σ_y = Yield stress of material (N/mm^2)

σ_E = Ideal elastic buckling stress (N/mm^2)

The critical buckling coefficients m_1, can be calculated using the equations below from ref [3].

For plates with longitudinal framing:

$$\text{For } \sigma' = \sigma \qquad m_1 = 4; \qquad (3.5)$$

For plates with transverse framing:

$$\text{For } \sigma' = \sigma \qquad m_1 = C_2[1+(s/l)^2]^2; \qquad (3.6)$$

Where: m_1 = Plate distribution factor

s = Small side of plate

l = Large side of plate

C_2 = 1.21 (Stiffeners are T-sections or angle bars)

3.3 Analysis

The analysis will assume standard plate lengths, widths, and buckling coefficients, thus only ideal elastic compressive stress for plates with longitudinal framing will be considered. The ABS guide for building and classing high-speed naval craft will be utilized to calculate the ideal elastic stress for aluminum plates with longitudinal framing, which is the current industry standard for high-speed ships. The aluminum ideal elastic stress will then be used to solve for required plate thicknesses for each material. Because cost and weight are extremely important in future naval ship design acquisitions, only cost and weight of each material will be compared under the same ideal elastic uni-axial compressive load. Normalization of the values will be done using the non-linear

normalization process outlined in section 2.4.2. The process is intended to demonstrate the MDL method's versatility and how it can be exploited to solve for a vast number of structural design issues for light-weight ships.

The following assumptions are made to calculate the ideal elastic compressive stress, σ_E, for aluminum 5086 H34:

- $m_1 = 4$ (Eqn. 3.5)
- $E = 6.9 \times 10^4$ N/mm^2 (Converted from Table 2.1)
- $t_b = 10$mm (Reference plate thickness)
- $s = 1000$mm (Reference short side of plate)
- $l = 3000$mm (Reference long side of plate)

Using Eqn. 3.2 and solving for the ideal elastic compressive stress for Aluminum:

$$\sigma_E = 24.86 \text{ N/mm}^2$$

Given the assumptions above, Eqn. 3.2 can be modified to solve for plate thickness, t_b for the other light-weight materials:

$$t_b = s\sqrt{\frac{\sigma_E}{0.9Em_1}}; \qquad (3.7)$$

Table 3.2 shows the calculated values for plate thicknesses and volume of each of the light-weight materials given the geometric plate assumptions above.

Material	Thickness t_b (mm)	Volume (mm^3)
Grade A Steel	5.82	1.75E+07
Single Skin Aluminum (A5086-H34)	10.00	3.00E+07
Aluminum Sandwich (honeycomb core)	10.00	3.00E+07
LASCOR Steel	5.82	1.75E+07
Composite (CFRP) Carbon w/ Vinyl Ester Resin	6.18	1.85E+07
DUCTAL © (UHP2C)	11.31	3.39E+07

Table 3.2: Thickness and Volume Requirements for Equal Uni-Axial Compressive Load

Now that a comparison of volume is complete, the values for pure cost and weight can be calculated in order to create the quantitative comparison table for the MDL analysis. Table 3.3 contains the calculated values for the material plating cost and weight based on respective ($/kg) and (g/cm^3) values.

Material	* Material Cost ($/kg)	Density (kg/mm^3)	Cost ($/panel)	Weight (kg/panel)
Grade A Steel	2.56	7.80E-06	348.17	136.14
Single Skin Aluminum (A5086-H34)	3.64	2.66E-06	290.40	79.83
Aluminum Sandwich (honeycomb core)	6.02	1.80E-06	325.14	54.02
LASCOR Steel	22.05	5.20E-06	2000.99	90.76
Composite (CFRP) Carbon w/ Vinyl Ester Resin	26.46	1.60E-06	784.37	29.65
DUCTAL © (UHP2C)	0.95	2.50E-06	80.40	84.81

* Specific material references provided in reference section of thesis

Table 3.3: Cost and Weight of Panel Given Equal Compressive Load Requirements

As with the design of any system it is imperative to understand what characteristics are desired from the material, so the MDL method will be used to solve for the optimum material in which three cases are examined. The first case will be for a designer preference of light weight materials, the second case will be for a designer preference of low cost materials, and finally the last case will be for an equal preference between weight and cost.

3.3.1 Light Weight Preference

As mentioned in the previous section, the first case to evaluate is for a designer's preference of weight. The MDL table is provided below.

Goals	Positive Decisions	Weighting Factors, α	Critical Value, X_c
Light Weight	3	.75	290.40
Low Cost	1	.25	79.83

Table 3.4: MDL Table for Case #1

Using the non-linear normalization process from section 2.4.2, the following normalized values are calculated. The normalized values are the same for all three cases because the non-linear scaled normalization values and critical values remain the same.

Material	Weight (kg)	Cost (kg)
Grade A Steel	-11.25	-35.24
Single Skin Aluminum (A5086-H34)	0.00	0.00
Aluminum Sandwich (honeycomb core)	-7.10	33.93
LASCOR Steel	-78.11	-9.60
Composite (CFRP) Carbon w/ Vinyl Ester Resin Longitudinal Direction	-51.25	100.00
DUCTAL © (UHP2C)	100.00	-4.62

Table 3.5: Non-linear Normalized Values

Using the weighting factors from Table 3.4 and the normalized values from Table 3.5, the performance index can be calculated to provide the ranking of the materials based on cost and weight, given the preference for light weight materials.

Material	Performance Index, γ	Rank
Grade A Steel	-29.24	6
Single Skin Aluminum (A5086-H34)	0.00	4
Aluminum Sandwich (honeycomb core)	23.67	2
LASCOR Steel	-26.73	5
Composite (CFRP) Carbon w/ Vinyl Ester Resin Longitudinal Direction	62.19	1
DUCTAL © (UHP2C)	21.53	3

Table 3.6: Material Selection Based on Weight Preference

Table 3.6 shows that when cost is preferred the results are slightly different than the results obtained in Table 2.10 in which more attributes were considered than just cost and weight. This makes sense due to the fact that cost and weight are the two top priorities of the designer and thus most heavily weighted. Additionally, the results should be the same or very close because in the initial assessment weight was the highest priority in the design of high-speed craft.

3.3.2 Low Cost Preference

The second case to evaluate is for a designer's preference of low cost materials. The MDL table is provided below.

Goals	Positive Decisions	Weighting Factors, α	Critical Value, X_c
Light Weight	3	.25	290.40
Low Cost	1	.75	79.83

Table 3.7: MDL Table for Case #2

Using the weighting factors from Table 3.7 and the normalized values from Table 3.5, the performance index can be calculated to provide the ranking of the materials based on cost and weight, given the preference for low cost.

Material	Performance Index, γ	Rank
Grade A Steel	-17.25	5
Single Skin Aluminum (A5086-H34)	0.00	3
Aluminum Sandwich (honeycomb core)	3.15	2
LASCOR Steel	-60.98	6
Composite (CFRP) Carbon w/ Vinyl Ester Resin Longitudinal Direction	-13.44	4
DUCTAL © (UHP2C)	73.84	1

Table 3.8: Material Selection Based on Cost Preference

From the rankings in Table 3.8 it can be shown that when cost is preferred the results differ from those obtained when the designer's preference was for light-weight materials. Once again, the results are reasonable and show the lowest cost material, DUCTAL ©, as

the material of choice, while LASCOR steel ranks highest due to its extremely high costs for the equivalent compressive strength.

3.3.3 Equal Preference Between Cost and Weight

The final case is an evaluation for a designer's equal preference between light weight and low cost material given equivalent uni-axial compressive stress capability.

Goals	Positive Decisions	Weighting Factors, α	Critical Value, X_c
Light Weight	2	.50	290.40
Low Cost	2	.50	79.83

Table 3.9: MDL Table for Case #3

Using the weighting factors from Table 3.9 and the normalized values from Table 3.5, the performance index can be calculated to provide the ranking of the materials based on equal preference for cost and weight.

Material	Performance Index, γ	Rank
Grade A Steel	-23.24	5
Single Skin Aluminum (A5086-H34)	0.00	4
Aluminum Sandwich (honeycomb core)	13.41	3
LASCOR Steel	-43.85	6
Composite (CFRP) Carbon w/ Vinyl Ester Resin Longitudinal Direction	24.37	2
DUCTAL © (UHP2C)	47.69	1

Table 3.10: Material Selection Based on Equal Preference for Cost and Weight

When the designer indicates equal preference between low cost and light-weight attributes, a surprising development occurs as a non-traditional material is selected as the

optimum material. DUCTAL ©, an Ultra High Performance Concrete Composite (UHP2C) becomes the material of choice based on the attributes for comparison. This analysis presents exciting possibilities for UHP2C application in ship construction. The MDL method also reveals alternatives materials that can be used by comparing the performance index and selecting materials that are numerically close to the material that the designer is looking to replace (i.e. replacing single skin aluminum with a higher strength aluminum sandwich material).

Chapter 4. Technology Developments that Support the Use of Light-Weight Materials

4.1 Introduction

Although adequate structural performance is paramount for any material used in design, high-speed naval craft also require materials that provide survivability, reproducibility, and the ability to be effectively tested and evaluated through-out the ship's life. The advantage of traditional materials is that they are proven and predictable. Also, the technology to improve and evaluate traditional materials such as steel and aluminum is readily available and cost effective. However in the past, when using composites, hybrids, metal and composite sandwich structures, and/or other experimental materials such as ultra-high performance concretes, the predictability of how these materials endure in the harsh operational environments was dubious. Not knowing how these materials performed in the harsh marine environment during high speed operation increased the risks of material failure in terms of cost and safety.

Fortunately, the technology that supports the use of advanced materials in high-speed craft operation in most cases exists or is currently being developed. In particular, the areas of fire protection, improved manufacturing and production techniques, and non-destructive testing (NDT), have seen significant advances that demonstrate that new materials and various material configurations have similar operational performance reliability as traditional materials.

Although the new technology tends to add to the overall cost of advanced materials, the additional cost may be justified depending on the application and benefits as in the case of weight-critical ships.

4.2 Fire Protection

Although no material is impervious to indefinite exposure to fire, some materials are more durable than others. In particular, composites and aluminum tend to have degraded fire protection performance when compared to steel. Also, composites and thinner structures such as the face sheets for sandwich constructed panels which tend to be used in light-weight ship construction are also less durable. Currently the U.S. Navy uses bat or fibrous insulation blankets to increase fire resistance of structural members for steel and aluminum.[26] Although insulator coverings do in fact provide increased survivability against fire, these are labor intensive to install and are not practical for covering structural members such as stiffeners and support framing. Fire retardant resins are mildly successful at making composites more fire resistant, however their application often increases cost than and may change the desirable mechanical properties of the material.

In order to improve upon the existing fire resistances of composites and aluminum to provide a similar level of fire resistance when compared to steel, spray-applied passive fire protection systems are being used and developed.[26] A spray-applied fire retardant has several benefits over the traditional bat protection coverings and fire retardant resins.

Advantages of spray-applied passive fire protection systems

- Applied at manufacturing facility or shipboard
- Light-weight
- 100% coverage
- Tailored to meet specific requirements (types of coatings and thickness)
- Durable and provide long term fire resistance
- Little or no limitations on surfaces to which it can be applied
- Can be applied to steel, aluminum, and composites

Spray-applied fire retardant technology for use in naval architecture is still in the early stages of development, however its application has shown promising results for increasing fire protection of composites and aluminum. Some issues associated with the fire resistant sprays include, impact durability, vibration resistance, insufficient fire resistance capability for some applications, and high costs. The following tables show several spray-applied fire retardants and insulators along with their associated characteristics.

Parameter	Coating Characteristic
Product Name	Dendamix marine
Composition	Blended Fiber Products
Primary Application	A60 and thermal insulation for steel
Use on Ships	Approved for use on decks and bulkheads
Advantages	Low cost, made with recycled products
Disadvantages	Application consistency, durability

Table 4.1: Dendamix Marine Coating Characteristics [26]

Parameter	Coating Characteristic
Product Name	FASTBLOCK ® 810
Composition	Water-based, sprayable fire and thermal barrier coating
Primary Application	Thermal barriers for extreme heat flux environments such as sensitive materials in weapons systems, containers, aircraft, and ships
Use on Ships	Under consideration for future naval platforms
Advantages	Proven fire resistance to UL1709 fire insulation, durability
Disadvantages	High cost

Table 4.2: FASTBLOCK ® 810 Coating Characteristics [26]

Parameter	Coating Characteristic
Product Name	A-18 NV Fire Protection Intumescent Coating
Composition	Non-flammable water based intumescent coating. Upon exposure to flame or heat, it immediately foams and swells (intumesces) providing an effective insulation and heat shield to protect subsurfaces.
Primary Application	Substitute for ordinary paints to improve fire performance
Use on Ships	Approved as fire-retardant paint
Advantages	Easy application, low cost and weight
Disadvantages	Insufficient fire resistant properties. Must be used in conjunction with other fire suppressant systems

Table 4.3: A-18 N Fire Intumescent Coating Characteristics [26]

Parameter	Coating Characteristic
Product Name	Thermo-Lag 3000
Composition	Epoxy based coating
Primary Application	Structural columns, beams, vessel skirts, bulkheads, underdecks and electrical raceways
Use on Ships	ABS, Lloyds and DnV certificates for hydrocarbon fires
Advantages	Thin application of product required
Disadvantages	Possible toxic smoke potential due to epoxy

Table 4.4: Thermo-Lag 3000 Coating Characteristics [26]

4.3 Improved Production Techniques

Until recently U.S. shipyards have been primarily geared toward the manufacturing and production of steel ships. Not much emphasis was placed on lightweight materials and the processes which are required in their construction. Thinner steel and aluminum plating, composites, and sandwich materials require different manufacturing processes which lead to higher costs, longer production time, and higher levels of quality control. Because of intrinsic geometry and physical property differences between heavier steel construction and lightweight material construction, the manufacturing industrial base must to change. Not to say that the entire manufacturing process must be reinvented but rather it should be modified and improved to support efficient and cost effective light weight material production.

Over the past decade marked improvements have been made in the following areas of production techniques that have reduced lightweight material costs and allowed for their increased use and application [27]:

- Material handling and stowage - Ensure pre-construction materials are placed on hard flat decks to prevent bowing and fatigue stresses from deformation.

- Composite Filament Winding – Improvements in composite manufacturing in terms of automation, speed, variable thickness, and control of resin flow and void reduction.

- Forming, Stamping, Injection Molding, and Rolling – Higher volume of composite material production is achieved with increased consistency and accuracy of the aforementioned processes during the last several years. Automation has increased and overall costs of manufacturing have decreased.

- Precision cutting and panel assembly - Laser cutting materials assists with controlling consistent accuracy of panels and minimize distortion of pre-assembly pieces. Also, assembling panels with flat side up allows for easier joining of the materials and reduces finished product residual stresses.

- Prefitting of stiffeners - Sequential pattern welding of stiffeners and fillet welds reduces fatigue stresses and distortion from welding.

- Precision high-speed welding - Reduces overall production time through the elimination of rework. Also, provides increased pre-fit optimization and consistency in welding.

- Use of Transient Thermal Tensioning (TTT) based distortion prediction – Induces local plate tensioning by applying heat source locally, thus reducing compressive in-plane stresses. "TTT is advantageous in any area where buckling would be likely to create severe plate deformation." [27]

- Reverse Arch Welding – The use of reverse arching leads to reduce residual stresses that develop under T-joints. Studies outlined in ref [27] also show that reverse arch welding reduces buckling and final distortion when welding T-stiffeners in ship plating.

4.4 Non-Destructive Evaluation (NDE) Innovations

New NDE techniques are emerging to allow for a wider evaluation of materials and sources of material degradation from cradle to grave. It is not the aim of this section to cover all of the latest technology and research that has been done, but rather to highlight the areas in which the NDE technology gaps that previously existed are being addressed and resolved. Material production is not an exact science. From the time the ingredients that make up a material are mined from the earth to the finished product, there exists many opportunities for inconsistencies and variations to occur in the materials uniformity. Thus, a system to test and evaluate a material is crucial to ensure that design requirements are met and maintained from the earliest stages of manufacturing to the end

of the operational life. Although numerous NDE methods already exist to achieve and maintain standards of quality that translate into increased safety, higher manufacturing standards, reliability, and longer product life, there still exist technology gaps in evaluating advanced materials such as composites, hybrid structures, and sandwich constructed materials.

Micro cracks are one of the root causes of many materials degradation over time and in some cases catastrophic failure. It is essential when using materials, in particular lightweight materials that may not be proven for a certain application, to ensure that they can sustain the static, dynamic, environmental, and impact loading over their respective design lifetime. One form of new technology that assists engineers and designers in evaluating the materials' micro-structural behavior is by Acoustic Emissions (AE) systems. AE systems basically measures the sound emitted from a material as it under micro-structural changes due to loading. The sound is digitized and converted to a quantitative scale that measures growing cracks, fibers breaking, any other active damage that occurs in the material.[28] Results from various materials under the same loads and conditions can be compared and evaluated. Also, existing material applications can be more closely examined and potential safety issues can be identified and addressed. Although there are some problems with background noise, AE technology can be used extensively in material analysis for high-speed naval craft and has the potential to reduce research and development times for using non traditional materials.

When a material is first selected and fabricated it is relatively straightforward to conduct quality control. The materials thickness, appearance, deformation, and even

microstructure can be tested and verified suitable for the application. However, once the material is in the operational arena and exposed to a multitude of loads including impact damage, the materials characteristics may change and it can be extremely difficult to measure the degraded effects. Materials such as composites, ultra high performance composite concretes, and even aluminum can be highly degraded in terms of performance as a result. The technology that can determine the degradation of these materials has been lessened through an innovative NDE technology that can be used to evaluate impact damage of lightweight materials is called Ultra High Frequency Focused Ultrasound (UHFFU). UHFFU can identify impact damage and bonded defects in composites, concretes, and jointed structures. [28] It works by emitting a UHF signal into the material by locating the precise location of micro-structural change which may include delamination in composites, cracks in concrete, or any other type of damage in a given material. The tool allows engineers to evaluate where a material tends to fail and under what conditions it fails. UHFFU can be used to generate data that can be feed back into a material selection process such as MDL, as proposed in this thesis, to provide a more insightful and optimized selection.

For analyzing layered materials such as composites, plastics, and other hybrid materials, a new technology called the Acoustic Optic Technique has been developed. This technique measures phase differences between ultrasound energy being bounced off the surface of a given material to check the quality of the surface or a very thin layered surface. "From numerical calculations it is seen that, even for low frequency ultrasound, the phase information is extremely sensitive to specific characteristics of layered materials only when ultrasound is incident in a critical angle of the investigated material."

[28] This technique also has other applications to materials evaluation such as measuring plate face roughness and hardness.

Lastly, an innovative NDE method to inspect the interior of complex structures is a technology called Microfocus Computer Tomography (MCT). It works by measuring differences between the absorption and attenuation of X-Rays through a material or object and providing 2D and 3D images of internal structures pinpointing any material issues. MCT has possible application in the internal inspection of lightweight and traditional materials including metals, alloys, composites, fiber reinforced concretes, sandwich constructed materials, and electronic components. It is also useful in the detection of corrosion, internal cracks, debris, and entrapped air bubbles and liquid. [28]

Chapter 5. Conclusion

5.1 Results Driven By Designer Influence

In this investigation of a proposed MDL material selection method for high-speed naval craft, it is important to note that the process is very dependent on parameters used for inputs and assumptions. Thus, a warning must be given that the MDL method along with non-linear normalization tends to make the designer's influence significant via attribute weighting factors. Although the MDL method is a great tool to use for initial material assessment, much research and development must take place in order to avoid unforeseen structural failure and material performance defects.

5.2 Conclusions

Over the last two decades there have been exciting new explorations into new materials, applications of existing materials, and more efficient fabrication techniques. With more materials available to designers it is now imperative to be able to quickly and accurately decipher which materials and alternatives to traditional materials can be used to optimize design of system. The investigation of using the MDL method for material selection of light-weight materials demonstrated the following results:

- The MDL method is specifically designed to integrate actual material characteristics and properties with the desirable end-product performance. What is unique about this method of material selection is that it integrates the "human" factor into the design process through the use of weighted factors assigned to

attributes based on the designer's preference. The material selection results are based on this algorithm and provide reliable and adequate initial assessment capability.

- Using referenced materials and desired quantitative and qualitative attribute weightings, the following ranking for material selection was obtained:

Material	**Rank**
Grade A Steel	6
Single Skin Aluminum (A5086-H34)	4
Aluminum Sandwich (honeycomb core)	3
LASCOR Steel	5
Composite (CFRP) Carbon w/ Vinyl Ester Resin	1
DUCTAL (HP2C) *	2

The results show that composites are the overall best material for high speed craft design. It is important to note that the results are not indicative of all craft and situations. For example, for craft greater than 100 m, composites may not have enough in-plane strength to safely carry the hydrodynamic and slamming loads for large vessels. As one can see the process is not perfect and is only as good as the designer's inputs, but the tool is still quite effective for initial design analysis.

- Non-linear normalization provides the ability for the results to be compared to a set of baseline criterion (critical values). In this case the criterion and attributes for single skin aluminum was used because it is the current U.S. Navy standard for light-weight material design for high-speed craft. Simply put, if the value of a given material's attribute is higher than the critical value it performs better than

the base criteria, if it is lower than the critical value than it performs worse. This gives the designer useful data to factor into the final selection.

- The analysis also demonstrated the utility of the MDL method to select alternative materials to replace existing materials given the similar design requirements and attribute weights. This can be done by selecting materials with the performance indices that are close in value to each other. The closer the performance indices the more alike the two materials. This is a useful tool for selecting materials that perform the same, but for example, have different fabrication costs or required manufacturing skill level.

- The MDL method is versatile and can be used for a variety of structural applications in the field of Naval Architecture. In particular, the study elucidated the versatility of application by selecting the best material for plate panels when considering only uni-axial compression loading in terms of cost and weight. Although, it is agreed that to base a final material selection decision on only one attribute alone is not wise, the process demonstrated how the decision process can be tailored to any design problem large or small.

- The results show that the MDL method is a great tool to examine non-traditional materials and see how they perform against more tired and true materials such as steel and aluminum. In this case, DUCTAL ©, which is an ultra-high performance concrete showed promising results when considering its application in uni-axial loaded structural members. Although the material has been used in civil engineering applications, it has exciting potential for use in Naval

Architecture due to its light-weight, strong, inexpensive, and anti-corrosive characteristics.

- It was also apparent from the research that a material selection process alone is not enough to predict operational and life-cycle performance of a given material. The process to implement a new material is very labor intensive, time consuming, and expensive.

- Risks are high when using new materials or materials that haven't been proven for a new application. To adequately address the structural aspects of materials a finite element analysis must be conducted prior to final selection. Also long term research is required to sufficiently test and evaluate new materials.

- The best characteristic about the MDL method for material selection of light-weight materials is that it is simple and can be applied to any material and application. It is also a great tool for determining whether materials meet general requirements.

5.3 Suggestions for Future Research

The process of material selection is not an exact science and there will always be room for improvement. One aspect of Materials Science that can be predicted without question is the fact that the selection process in terms of new materials, construction techniques, and applications will always be a never-ending challenge for engineers and designers.

Some areas recommended for future investigation include:

- Comparison studies with other proven Multi-Criteria Decision Making (MCDM) methods to evaluate consistency between processes and material selections.
- A more thorough analysis of ship structures can be done to see if the same results are achieved that optimize application. Special attention should be directed to the construction process as well as material.
- Incorporate Finite Element Analysis (FEA) software to elucidate structural analysis of actual components. An integration of the MDL selection process with FEA can further enhance a designer's optimization of material.
- A closer look into technical challenges and gap identification can be explored, and how it can affect material selection results.
- A sensitivity analysis can be done of attribute data to determine the effects. In particular on the qualitative attributes such as fire resistance, repairability, resistance to corrosion, fabrication costs, and risk.
- In this investigation several different materials were compared. A future study can take a "micro" and "macro" review of the application of just one material. For example, the MDL method can be used to evaluate and compare different types of composites or laminates.
- Apply MDL to other aspects of the marine engineering field such as pre-fit manufacturing, ship repair and maintenance, or acquisition.

- Lastly, a further investigation into the use of ultra-high performance concrete composites in Naval Architecture is warranted due to their low cost, ease of repairability, ease of fabrication, flexibility in design, and structural performance.

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